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General Technical
Report RM-149

Management of Subalpine Forests: Building on 50 Years of Research

Proceedings of a Technical Conference

Silver Creek, Colorado

July 6-9, 1987

Erratum

This table was left out of: Finch, Deborah M. 1987. Bird-habitat relationships in subalpine riparian shrublands of the central Rocky Mountains. p. 167-172. *In:* Troendle, Charles A., Merrill R. Kaufmann, Robert H. Hamre, and Robert P. Winokur, technical coordinators. Management of Subalpine Forests: Building on 50 Years of Research. USDA Forest Service General Technical Report RM-149, 253 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

The first reference to it appears on page 169 of this article.

Table 2. Means + standard errors of 13 habitat variables for all random sites and 4 subalpine bird species. Significance of nested design ANOVA results that tested for habitat differences between random and species locations (BIRD effect) among 7 plots (PLOT effect) are indicated for BIRD effect in the Mean column: *$P < 0.05$; **$P < 0.001$; ***$P < 0.0001$. Correlation coefficients and significance levels for the relationship between spot-map densities (3-year mean) and mean habitat characteristics on 7 plots are given for each bird species. ANOVA significance results examining habitat variation among species (SPECIES effect) and between all birds and random sites (ALLBIRD effect) also are reported.

	Random (N=280)	Wilson s Warbler (N=28)		Song Sparrow (N=28)		Lincoln s Sparrow (N=59)		White-crowned Sparrow (N=24)		ANOVA	
Habitat variable	Mean	Mean	r	Mean	r	Mean	r	Mean	r	Species effect	Allbird effect
Vertical Foliage Density[1]											
Surface Layer	2.87 ± 0.11	3.29 ± 0.37***	0.58	2.75 ± 0.40	0.15	3.27 ± 0.26	0.81*	3.15 ± 0.39***	0.04	N.S.	N.S.
Low Shrub Layer	1.54 ± 0.09	1.75 ± 0.23***	0.73*	1.82 ± 0.35*	-0.24	1.32 ± 0.15*	0.31	1.72 ± 0.29***	0.34	N.S.	**
Tall Shrub Layer	0.55 ± 0.07	0.30 ± 0.11	-0.46	1.09 ± 0.21	0.87*	0.41 ± 0.11	-0.40	0.19 ± 0.10	-0.51	N.S.	N.S.
Effective Veg. Height (m)[2]	0.57 ± 0.03	0.93 ± 0.08***	0.73	1.35 ± 0.16***	-0.31	0.92 ± 0.09***	0.28	0.86 ± 0.09**	0.43	*	***
Percent Canopy Cover	9.24 ± 1.33	0.00 ± 0.00	-0.70	20.18 ± 4.16*	0.86**	8.68 ± 2.99	-0.47	1.04 ± 1.04	-0.75*	N.S.	N.S.
Percent Ground Cover[3]											
Shrubs < 1 m	28.17 ± 2.74	44.32 ± 6.51***	0.56	35.61 ± 5.64*	-0.69	31.98 ± 3.77	0.49	45.88 ± 6.73***	0.37	*	*
Grass/Forbs	52.49 ± 3.24	37.00 ± 6.17***	-0.77*	37.81 ± 6.01*	0.76*	45.64 ± 4.12	-0.42	39.04 ± 7.38	-0.64	*	N.S.
Woody Cover	43.32 ± 2.82	58.18 ± 6.40***	0.84*	50.36 ± 5.90*	-0.77*	43.83 ± 4.07	0.59	55.79 ± 6.77***	0.65	N.S.	N.S.
Bare Ground	5.57 ± 0.87	2.14 ± 0.88*	-0.43	5.79 ± 3.05	0.05	5.42 ± 1.39	-0.72*	0.50 ± 0.50	0.02	*	N.S.
Shrub Characteristics											
Crown Diameter (m)	1.33 ± 0.05	1.23 ± 0.11***	0.04	1.55 ± 0.20*	0.49	1.38 ± 0.08	0.42	1.45 ± 0.16	-0.40	***	N.S.
Dispersion (m)[4]	4.57 ± 0.35	2.01 ± 0.33	-0.26	2.69 ± 0.84	0.24	2.63 ± 0.30*	0.05	3.02 ± 0.42*	-0.09	***	*
Height (m)	1.73 ± 0.05	1.64 ± 0.33***	-0.18	2.00 ± 0.16	0.85*	1.59 ± 0.07	-0.11	1.40 ± 0.06	-0.58	***	N.S.
% Fruiting Shrubs[5]	11.25 ± 1.35	1.79 ± 1.79	-0.45	12.50 ± 3.96	0.12	3.39 ± 1.12*	-0.75*	4.17 ± 4.17***	0.10	N.S.	*

[1] *Vertical foliage density is the mean number of vegetation contacts falling against a vertical rod marked in intervals: < 0.3 m (surface), 0.3-1 m (low shrub), and 1-2 m (tall shrub).*

[2] *Effective vegetation height is the height at which a 20-cm wide board is > 90% obscured by vegetation at a distance of 5 m (Wiens 1969).*

[3] *Ground cover variables do not sum to 100% because the variable "Woody Cover" is a conglomerate that includes shrubs < 1 m, as well as larger shrubs, saplings, trees, and downed wood. Also, percentage water cover was not included because it was not significant in any tested relationship.*

[4] *Shrub dispersion is the mean distance (m) to nearest shrub (≥ 1 m tall) in each quadrant.*

[5] *Other than fruiting shrubs, woody vegetation was composed primarily of willow species.*

USDA Forest Service
General Technical Report RM-149

December 1987

Management of Subalpine Forests: Building on 50 Years of Research[1]

Proceedings of a Technical Conference

Silver Creek, Colorado

July 6-9, 1987

Technical Coordinators:
Charles A. Troendle
Merrill R. Kaufmann
R. H. Hamre
Robert P. Winokur

[1]These proceedings were compiled and produced in cooperation with the Society of American Foresters, and also are designated as their publication number SAF 87.08.

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Foreword

This summer marked the 50th anniversary of the Fraser Experimental Forest. These proceedings are the tangible product of the technical conference called to summarize, discuss, and transfer the knowledge learned over these 50 years. Eighteen formal papers describe the status of our knowledge about the interactions among timber, water, and wildlife. These papers were designed to present a balance of perspectives between research knowledge gained, and how that knowledge is actually being applied by forest managesrs and other resource specialists.

To broaden the scope of the conference -- and these proceedings -- 25 poster papers were also presented describing research in the subalpine environment in other ecosystems or for other resources. In total, the collection of papers in this volume is a good summary of state-of-the-art in understanding and managing the subalpine environment.

These proceedings are not only a statement of where we have been and where we are, but also present a glimpse of where we are going. In the past, research and management have been most concerned with resource response to impact. Today, we are equally or more concerned with a broader scope of human interaction with the environment and resource response to any potential environmental changes caused by man. This concern is evident in many of the papers that deal with recent, current, or proposed research, and may very well provide the base for the next technical conference on subalpine ecosystems.

The technical coordinators of these proceedings particularly want to acknowledge Sam Krammes for his initial planning efforts, and the speakers and attendees for their active participation and input during the conference itself.

Authors have propvided copies of their papers in electronic media form to expedite publication. The views expressed in these proceedings are the authors., and do not necessarily represent those of the U.S. Department of Agriculture.

Solicited Papers

Rocky Mountain Station Director, Charles M. Loveless (left), and Robert R. Alexander, Project Leader and long-time scientist at the Fraser Experimental Forest.

Early History of St. Louis Creek and the Fraser Experimental Forest: A Narrative

Robert R. Alexander[1]

Abstract--The early history of the St. Louis Creek drainage and the Fraser Experimental Forest is described in a narrative. Included are the establishment of the National Forests in 1908, logging by railroad and flume, and logging camps in the early 1900s, acquisition of private lands, establishment of the Fraser Experimental Forest in 1937, construction of the headquarters complex, research activities from the early days of the Experimental Forest to the present, and personnel that have worked on the Fraser Experimental Forest in the past 50 years.

Before Establishment of the Fraser Experimental Forest

Although Indians, probably Utes and possibly Arapahos, undoubtedly entered the St. Louis Creek drainage from time to time before the arrival of the white man, they left little or no visible evidence of their presence. With the settlement of the West, however, miners and trappers came into the valley in the late 1800s. Numerous ruins of mine shafts and cabins attest to their presence.

The earliest recorded mining claims near St. Louis Pass date from the early 1900s. Most of the miners were looking for gold, but found lead, zinc, and silver. In addition to those claims near St. Louis Pass, early miners were active in the Iron and Mine Creek drainages (fig. 1). Mining continued on a limited basis in upper Mine Creek through the 1950s. However, the volume of ore extracted was never high enough to warrant extensive operations.

The Fraser Experimental Forest was withdrawn from mineral entry in the early 1950s, and today there is no mining activity on the Forest.

On May 12, 1905, that part of St. Louis Creek drainage that lies north of Sections 32, 33, 34, and 35, T1S, R76W, 6PM was set aside as part of the Leadville Forest Reserve. The Leadville Reserve included southern Grand County from Kremmling, Hot Sulpher Springs, Fraser, and east to the Continental Divide. On July 1, 1908, it became part of the Arapaho National Forest when that Forest was established. The land north of that line was in private ownership at the beginning of this century.

[1]Chief Silviculturist and Project Leader in charge of the Fraser Experimental Forest, Rocky Mountain Forest and Range Experiment Station. Station headquarters is in Fort Collins, in cooperation with Colorado State University.

Logging began in this area (now part of the Fraser Experimental Forest) in 1906. A standard gauge logging railroad was built from the sawmill (established in 1906) located above the town of Fraser into the area to remove the timber harvested. The area that is now part of the Fraser Experimental Forest was part of 5,000 acres of forest land owned or leased by the Middle Park Lumber Co., operators of the mill. Although most logs were transported to the mill on flatcars (fig. 2) for manufacture, some rough lumber milled on site also was hauled. The railroad grade followed the present main road from the town of Fraser to the hill above the bridge crossing St. Louis Creek, turned west along a bench, and then south into the area northwest of Sagebrush Flat about 1 mile from the present main road between the Fraser Experimental Forest and the town of Fraser (fig. 3).

The original stands in the area west of the present road south to Sagebrush Flat were mature mixed Engelmann spruce, subalpine fir, and lodgepole pine. They were logged until 1907, when sparks from the logging locomotive set the area on fire. After the fire, the area regenerated to lodgepole pine, and today it is stocked with second-growth lodgepole pine. Railroad logging in the general area continued until about 1912 when the lumber company went bankrupt. By 1918, the mill, railroad, etc., no longer existed. Although the railroad was abandoned and the rails taken up, and the mill dismantled, evidence of the old railroad grade and the concrete footings of the mill site can readily be seen today. The logging engine, a Climax, was left standing on a short stub-end siding at Fraser until 1939 (fig. 4).

To the east of the present main road, the land area in the St. Louis Creek drainage north of the original National Forest boundary was a combination of "school lands" and other private ownership. The original forests in this area also were

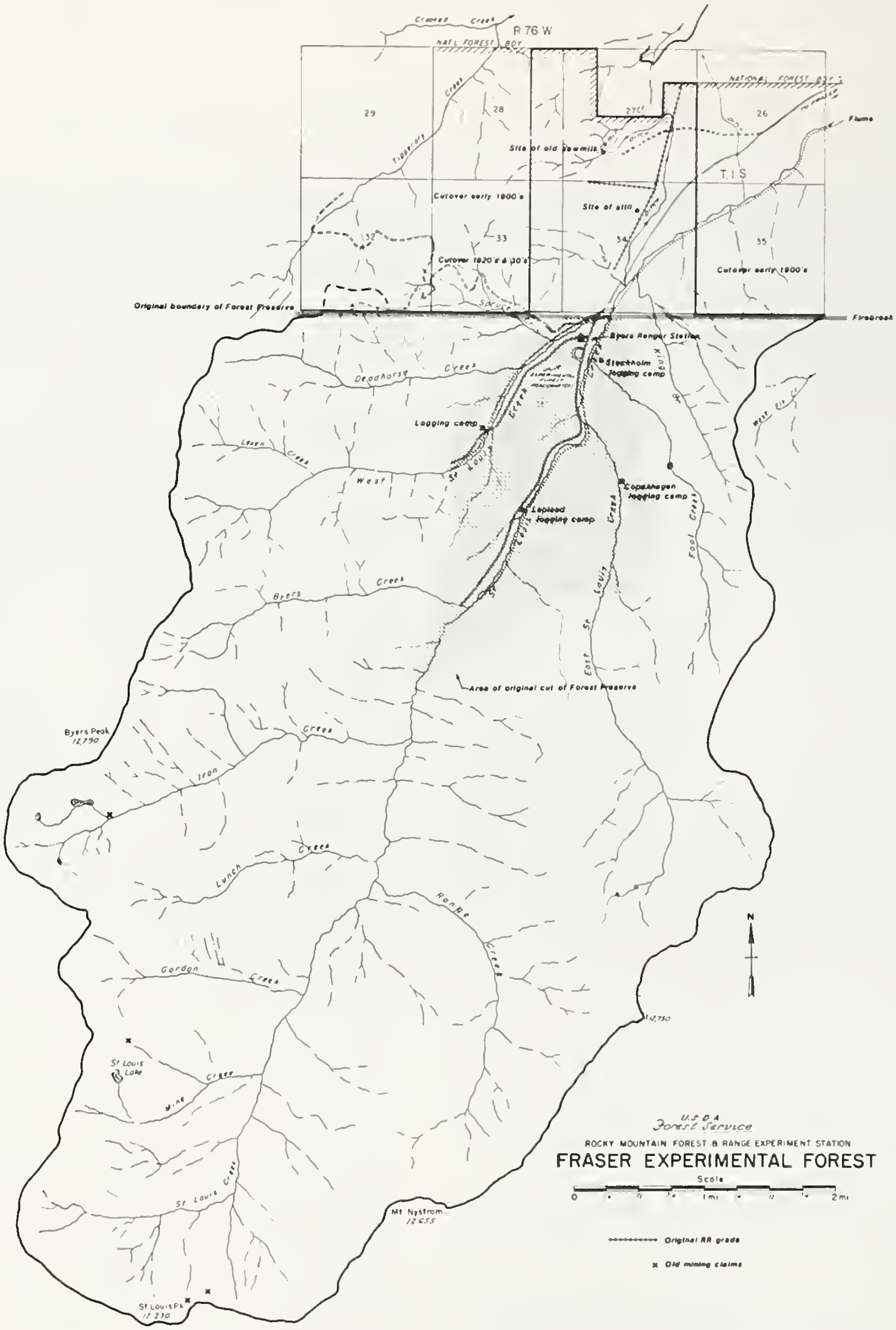

Figure 1.--Diagrammatic sketch of the St. Louis Creek drainage, showing location of streams, roads, physical structures, and mining and logging activity before establishment of the Fraser Experimental Forest.

logged over and burned. These lands regenerated to aspen and lodgepole pine, with the latter now crowding out the aspen.

Concern about the repeated fires in the areas north of the original forest boundary caused the early National Forest officers to cut a 600-foot wide firebreak from ridgetop to ridgetop along the north boundary of the National Forest lands sometime about 1910 (fig. 1). All trees were felled, and the usable material sold and removed. The firebreak, which regenerated to dense, second-growth lodgepole pine, can be identified today.

Most of the cutover and burned over lands below the original forest boundary were acquired by the Forest Service in a series of land exchanges between 1928 and 1930. In 1951, the last cutover private land, now within the boundaries of the

Figure 2. Loading logs at the end of the rail line. Note size of logs on the flatcars (1907).

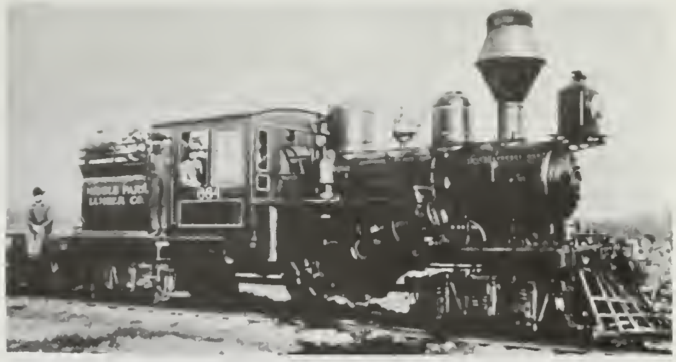

Figure 4.--Climax locomotive No. 684 used to haul log train from woods to the mill (1907).

Fraser Experimental Forest, was obtained from Koppers Co., Inc.

Early timber harvesting on the National Forest also began about 1910. These stands also were mature mixed spruce, fir, and lodgepole pine. Individual trees were marked and cut rather than following the clearcutting practices used on adjoining private lands. The original nails scribed with U.S. and the date used to designate cut trees can still be found in stumps where they were placed after the trees were cut.

During the early timber harvesting on Forest Service land, a flume was built from a mill, located just east of the present Koppers Co. yard and north of the town of Fraser, and extending along St. Louis Creek to just above its confluence with Byers Creek (fig. 5). A flume also was built from the confluence of St. Louis Creek and West St. Louis Creek along the latter stream for a distance of about 2 miles. Evidence of the flume and the structures used to dam water (fig. 6) still can be seen today.

Figure 3.--Diagrammatic sketch of area now occupied by second-growth lodgepole showing location of old railroad grade, irrigation ditches, roads, and research plots. This area originally was in private ownership.

Trees on the National Forest lands generally were in the 11- to 15-inch diameter class (i.e., material suitable for railroad ties). This partial cutting resembled a two-cut shelterwood. In areas near the flume, logs were cut, skidded by horses, and decked at landings along the flume where they could be loaded into the flume for transport to the mill (fig. 7). As cutting progressed away from the flumes, logs were either loaded into horse-drawn wagons for transport to the landings in the summer or into horse-drawn sleds in the winter (fig. 8). Logs decked during the winter were not flumed until water could readily flow through the flume without freezing. Judging from the extensive network of wagon roads still evident on the ground, most of the areas along all stream bottoms within skidding distance of the flume were cutover. During this period of time, some logs also may have been transported to the mill in wagons or sleds.

When logging began on the National Forest, logging camps were established at several locations. The camp at "Lapland" was located in the clearing about 1 mile south of the Fraser Experimental Forest headquarters, where the Denver Water Board's siphon crosses the main road (fig. 9); the camp at "Stockholm" was located in the clearing across St. Louis Creek east of the Experimental Forest headquarters; and the camp at "Copenhagen" was located in a clearing just below the present gaging station on East St. Louis Creek. The largest camp was "Lapland," which provided housing for both single and married loggers (fig. 10). These camps persisted until after World War I, but evidence of their existence has been obliterated, with the exception of the ruins of a cabin, stable, and cookhouse at Copenhagen. In addition, there were other more temporary camps. One of these was located on the site later occupied by the Byers Ranger Station. There are people still living in the Fraser area that were born in these logging camps.

There also is evidence of an old logging camp and two sawmill sets on Spruce Creek about 1 mile west of the present Fraser Experimental Forest headquarters. However, these remnants of early logging activity were in use as late as the 1930s when the land to the west and north of the camp and sawmill sets was in private ownership.

About 1915, the Byers Ranger Station was built in the clearing just north of the present Fraser Experimental Forest

Figure 5.--Wooden flume constructed to transport logs to the mill at Fraser.

Figure 6.--Headgate and dam constructed to provide the head of water needed to float logs in the flume.

Figure 7.--Logs decked near "Lapland" waiting transport to the mill by flume.

Figure 8.--Horse-drawn sled used to transport logs to landings in the winter.

Figure 9.--Logging camp at Lapland, 1917.

Figure 10.--The Frank Madison (left) and J. B. Stevens (right) families at Lapland (1917) ready for church.

headquarters. This station, occupied year long, consisted of a two-story house, barn, and outbuildings constructed from rough logs (fig. 11). The station, occupied until the 1930s, persisted until the 1950s, when all buildings but the log barn were either torn down or moved. The old barn, now used for storage, is the only visible remains of the station. The ranger assigned to this station was responsible for general administration of the area, including the establishment of an extensive system of trails that accessed the largely roadless area within the forest boundary. Today, many of the trails have been abandoned, but there still is evidence on the ground and an occasional trail sign.

As the Forest Service acquired those lands below the original forest boundary beginning in the 1920s, logging activity diminished, with the exception of those lands north of the forest boundary and west of the present main road that were owned by Koppers Co. This reduction was due largely to the fact that most readily accessible land had been cut over and/or burned over, and the market for railroad ties was poor. Logging on Koppers' lands, mostly for poles, continued until they were acquired by the Forest Service in the early 1950s in a land exchange.

Other activities occurred on lands north of the original forest boundary after they were acquired by the Forest Service but before the establishment of the Fraser Experimental Forest. During Prohibition, a still was established west of the present road about half way between the Fraser Experimental Forest headquarters and the present Experimental Forest entry sign (fig. 1). The operators distilled moonshine whiskey and stored it in barrels for resale. A disgruntled competitor or customer notified local law enforcement officers, who destroyed the still. The broken barrels, staves, and hops still are visible, scattered around the site.

Water always has been important to the ranches in the Fraser Valley. Three irrigation ditches transport water from St. Louis Creek west and north to ranchers for irrigation of heavy meadows (fig. 3). Today, all ditches are operational, but water carried by some of the ditches has been sold to the Denver Water Board.

Figure 11.--Byers Ranger Station. Location was just north of present Fraser Experimental Forest headquarters.

Both cattle and sheep allotments in force on the Fraser Experimental Forest predate establishment. The cattle allotment was for 55 AUMs for a number of years, but has been 23 AUMs in recent years. Cows and calves are turned onto the Experimental Forest by the permittee on July 1 and are removed by October 1. The sheep allotment (1,000 to 2,000 head band) is part of a larger allotment. Sheep normally are moved up the Darling Creek driveway, moved across the high county, and end up on the Fraser Experimental Forest before being removed down the Fool Creek driveway. In recent years, the permittee has chosen to take nonuse in 3 out of every 4 years.

After Establishment of the Fraser Experimental Forest

The McSweeny-McNary Act, passed by Congress in 1928, authorized 12 regional forest experiment stations. The Rocky Mountain Forest and Range Experiment Station, the last of the experiment stations funded by the Act, was established July 1, 1935. It is headquartered in Fort Collins, Colo., in cooperation with Colorado State University. Because it was the policy of the Forest Service to concentrate research work on experimental forests, the Rocky Mountain Station, with assistance from the officers of the Regional Forester and Supervisor of the Arapaho National Forest, selected the 23,000 acres of St. Louis Creek drainage as an area for research. On May 10, 1937, the report establishing the Fraser Experimental Forest was submitted, and on August 26, 1937, it was approved by the Chief of the Forest Service. Original efforts were concentrated on timber and watershed research. In later years, the scope of research activities on the Fraser Experimental Forest has been significantly expanded.

The objectives and results of studies conducted on the Fraser Experimental Forest are beyond the scope of this narrative. This information has been documented by Alexander and others in numerous publications listed under Research Published 1937-1985 of Alexander et al. (1985).[2]

The area set aside for research originally was called the St. Louis Creek Experimental Forest, but the name was changed to Fraser Experimental Forest before formal establishment. While the Experimental Forest is part of the Arapaho National Forest, it is administered by the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. The present Fraser Experimental Forest occupies all of the original Forest Reserve and lands west of the main road, and north along the road to the Arapaho National Forest boundary (fig. 12).

The first research personnel assigned to the Fraser Experimental Forest established a tent camp in 1937 on Byers Creek, just south of where it enters St. Louis Creek (fig. 13). The

[2]Alexander, Robert R.; Troendle, Charles A.; Kaufmann, Merrill R.; Shepperd, Wayne D.; Crouch, Glenn L.; Watkins, Ross K. 1985. The Fraser Experimental Forest, Colorado: research program and published research 1937-1985. Gen. Tech. Rep. RM-118. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 46 p.

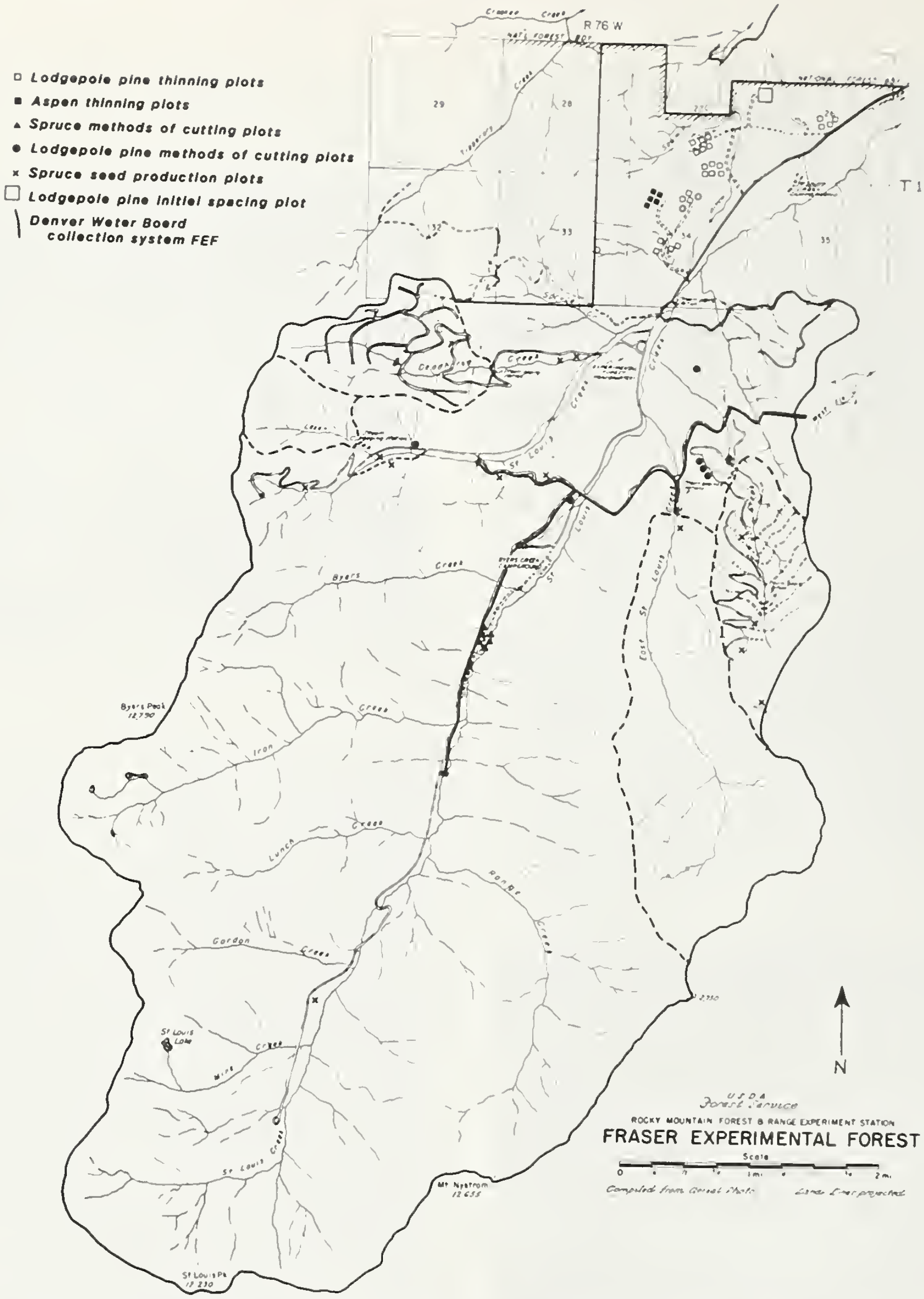

Figure 12.--Diagrammatic sketch of the Fraser Experimental Forest as it exists today showing locations of streams, roads, water diversions, other physical structures, and research plots.

original survey crew was primarily responsible for cruising and mapping early study areas, but they also staked and cleared the site for the present headquarters and cut and peeled the first logs hauled to the site for construction of the buildings.

In 1938, a CCC camp was established on the present site of the Fraser Experimental Forest headquarters. It consisted of barracks, a cookhouse, recreation hall, lavatory, and numerous storage and service buildings. Enrollees at this camp were responsible for cutting and milling most of the logs used to construct the two-bedroom house, the two single-bedroom houses, and the log garage that are still part of the headquarters complex (fig. 14). The buildings were constructed between 1938 and 1940 by local skilled artisans (carpenters, brick layers, etc.) employed by the Economic Recovery Administration (ERA). Original plans called for additional housing and storage buildings, but with the advent of World War II, the camp and the CCC and ERA programs were dissolved.

The original access to the headquarters area was a single lane road from the town of Fraser that paralleled the current road. This old road was frequently impassable during wet weather. The present all-weather two lane road was constructed in 1946-47 by the Public Highway Department.

After the CCC camp closed, one barrack, the cookhouse, recreation hall, and lavatory were retained for use by temporary summer field assistants hired to assist scientists in their work. The recreation hall collapsed in the late 1940s, and the

Figure 13.--Tents were used to house research personnel before construction of permanent housing at Fraser Experimental Forest headquarters. This tent was located at the Byers Creek site.

Figure 14.--Areal view of headquarters complex, Fraser Experimental Forest.

barrack, cookhouse, and lavatory were either demolished or moved in 1956, when the present dormitory and lounge were built. The office building was obtained from the Bureau of Reclamation in 1952 and located at its present site. Log siding was added to the frame building to blend in with the other log buildings. The metal garage in the work area was erected in the early 1960s, the log records storage building, originally a survival cabin, was moved from its site south of the old Fool Creek gaging station and placed at its present location in 1984, and the cookhouse and laboratory buildings were prefabricated and located on site in 1985 and 1986, respectively.

One of the original research efforts on the Fraser Experimental Forest was to locate and inventory the lodgepole pine methods-of-cutting plots on King Creek. These plots, consisting of five cutting treatments replicated four times, occupied 160 acres (fig. 15). Plots were harvested by ERA crews in 1939-1940. Trees were cut and the logs skidded by either horses (fig. 16) or tractors (fig. 17) to landings. Logs then were either transported by trucks to a local mill in Winter Park or milled on site by ERA crews with a portable sawmill (fig. 18). Access to these plots was provided by the King Creek Loop road, which was reconstructed in the late 1940s to its current standard.

A number of the original lodgepole pine methods-of-cutting plots in Block C along the upper loop of the King Creek road were obliterated in the early 1980s, when three large, 10- to 30-acre, clearcut units were installed to measure the effects of snow deposition in large openings (fig. 19).

In the early 1940s, the West St. Louis Creek road was constructed to the first switchback below the present access road to the Lexen Creek gaging station. This road originally was built to access Block I of the spruce-fir methods of cutting study. Block I, consisting of three treatments (fig. 20) and

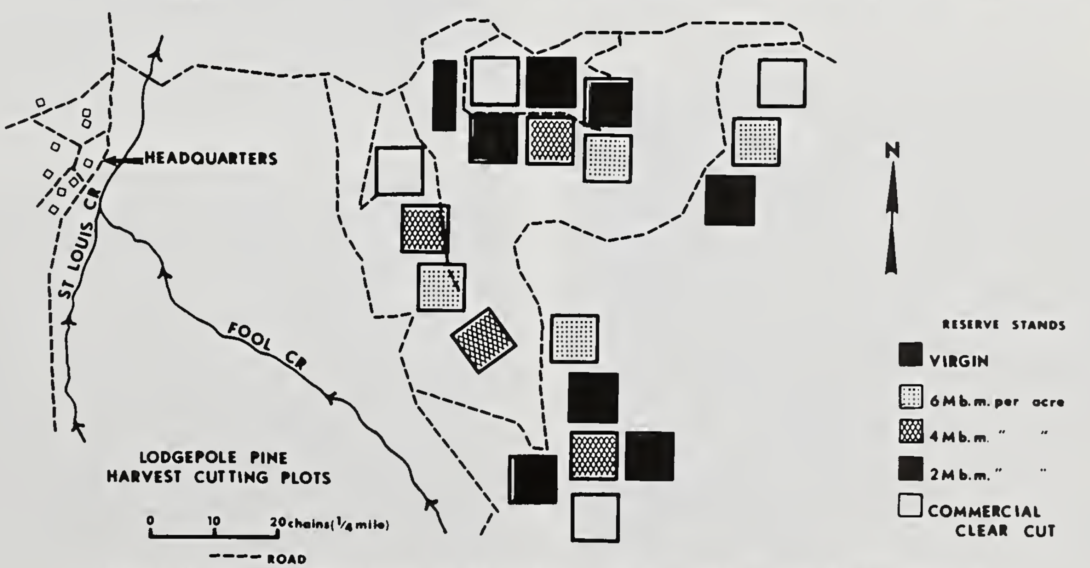

Figure 15.--Diagrammatic sketch of the location of the original lodgepole pine methods of cutting study on King Creek.

Figure 16.--Skidding logs with a horse on the lodgepole pine methods of cutting plots on King Creek in 1939.

Figure 17.--Tractor used to skid logs on the lodgepole pine methods of cutting plots on King Creek in 1939.

Figure 18.--Portable sawmill used to mill logs on site on the lodgepole pine methods of cutting plots.

Figure 19.--Large clearcut unit on the Fraser Experimental Forest cut to measure effects of snow deposition in large openings.

Figure 20.--(A) two-step shelterwood, (B) group selection, and (C) alternate strip clearcutting, Fraser Experimental Forest.

uncut control occupying 24 acres, was cut in 1944 by POWs from a camp established near the town of Fraser. The POWs employed were mostly Bavarians from Rommel's Africa Corps, who had considerable woods experience. The logs were bought by and transported to the mill in Winter Park. Construction of the West St. Louis Creek road, including the loop, was completed in the early 1950s. This road originally was intended to provide access to Blocks II and III of the spruce-fir methods of cutting study. However, the blocks were never cut. Today, the road provides part of the access to the Byers Peak and Bottle Pass trails.

The first watershed study on the Fraser Experimental Forest involved the paired Fool Creek and East St. Louis Creek watersheds. The treated watershed (Fool Creek), a 714-acre drainage, has been gaged since 1940. The original streamgage was replaced in 1980. The streamgage on the control watershed (East St. Louis Creek), a 2,198-acre drainage, originally was constructed in 1942 and reconstructed in 1965. The original access road to the Fool Creek streamgage was built in 1940 and reconstructed in the late 1940s. The current Fool Creek road system, 4.5 miles of main road and 8 miles of spur roads, was constructed in the early 1950s (fig. 12). Today, only the main road is maintained. Fool Creek was harvested in 1954-56 by removing timber in alternate cut and leave strips that varied from 66 to 400 feet in width (fig. 21). Logs were skidded with horses, decked, and saleable material hauled by truck to the Koppers Co. mill yard in Fraser. Unsaleable pulpwood products were decked in a clearing near the first switchback above the gaging station on the main road. This material was sold later as firewood to local motel and condominium operators.

In 1955-56, streamgages were constructed on another pair of watersheds on the west side of Fraser Experimental Forest. The treated watershed (Deadhorse Creek) is a 667-acre drainage; the control watershed (Lexen Creek) is 306 acres in size. The access road from the West St. Louis Creek road to the Deadhorse Creek main streamgage was built in 1955 and that to the Lexen Creek gaging station in 1956. The remaining access roads into Deadhorse Creek (approximately 9 miles of main and spur roads) were constructed from the early 1970s to the early 1980s (fig. 12). Two additional streamgages were built in the early 1970s, one on the North Fork and one on the Upper Basin. The first timber harvesting on Deadhorse Creek was in 1977-78, when the 100-acre North Fork unit was harvested by clearcutting about one-third of the subdrainage in small 3-acre clearcut patches. The North Slope unit, another 100-acre subdrainage, was harvested in 1980-81, when about one-third of the volume was removed in the first cut of a three-step shelterwood. The last unit harvested was the Upper Basin, a 200-acre subdrainage, where about 30% of the area was harvested in 1982-84 in small 1- to 5-acre clearcut patches (fig. 22). In all of these units, logs were skidded downhill to landings using rubber-tired skidders and small crawler tractors. Logs were hauled by truck to the mill in Fraser.

In 1955, the Denver Water Board constructed its water collection system on the Fraser Experimental Forest. Water, collected from all streams except Deadhorse and Spruce Creeks, is diverted by a series of gated structures into a collection system consisting of buried concrete and steel pipes varying in diameter up to 6 feet. Water is transported through this system into a 1,700-foot tunnel on King Creek and into the Vasquez Creek collection system for eventual transport through the Moffet Tunnel. Part of the present Fraser Experimental Forest road system is constructed over the Denver Water Board Diversion system (fig. 12).

A skyline cable system for logging steep slopes was tested from 1956 to 1959 on the Fraser Experimental Forest (fig. 23). The site was located on West St. Louis Creek, and the cableways from the three settings used are still visible to the west from the road just above the turnoff to the Lexen Creek gaging station (fig. 24). Trees were removed from slopes of 25% to 80%, a distance of one-half mile from the main landing, by both clearcutting and partial cutting.

In the early days, the Fraser Experimental Forest was considered a "back country station," and the Forest employed a cook during the summer months. From 1945 through 1960, when the government mess was discontinued, the cook was Andrew J. O'Malia. A sign "Ike Ate Here" hangs over the entrance to the dining room of the "lodge" at the Fraser Experimental Forest. President Dwight D. Eisenhower was a guest at the Byers Peak Ranch at Fraser, Colo., for part of the summers of 1953, 1954, and 1955. The Experimental Forest joins the west boundary of the ranch.

During the summer of 1953, arrangements were made with Sherman Adams (formerly a lumberman), Special Assistant to President Eisenhower, for the President to visit and have lunch

Figure 21.--Paired Fool Creek and East St. Louis Creek watersheds after strip cutting on Fool Creek was completed in 1956.

Figure 22.--Paired Deadhorse and Lexen Creek watersheds after timber harvesting on Deadhorse Creek was completed in 1984.

Figure 23.--Turn of logs being transported to the landing by skyline cable system, 1956.

at the Experimental Forest. President Eisenhower also was considered to be a good "camp cook." He and Andy became friends, and that lead to Eisenhower's introduction to then-Chief Dick McArdle at the dedication of the Missoula, Mont. fire lab in 1954.

Figure 24.--Cable logging site after system was removed showing cableways and timber harvesting patterns.

In the 50 years since the establishment of the Fraser Experimental Forest, about 50 scientists and a dozen technicians, permanent staff, and support personnel at Rocky Mountain Station, have been assigned to work on the Forest. (They are listed at the end of this paper.) In addition, nearly 100 scientists have worked there as either summer field assistants or as graduate students. During this time, more than 240 publications, Ph.D dissertations, and Masters theses have been produced from research done on the Forest (Alexander et al. 1985). Moreover, scientists from all over the United States and many foreign countries have visited the Fraser Experimental Forest to learn about research accomplished and underway.

In recent years, new areas on the Fraser Experimental Forest have been cut and thinned for studies (fig. 25) and demonstrations (fig. 26) that are part of the current research program. These activities and other studies underway are documented in papers presented in this symposium and in numerous publications listed by Alexander et al. (1985).[2]

Figure 25.--Young lodgepole pine thinned to GSL 120, Fraser Experimental Forest.

Figure 26.--Three-cut shelterwood demonstration area in old-growth spruce-fir, Fraser Experimental Forest.

Appendix1.--Personnel at the Fraser Experimental Forest.

Hydrology and soils	Timber	Wildlife and forest pests	Technician	Cook	Original survey crew
Jim Bergen	Bob Alexander[1,2]	Glenn Crouch[2]	Walt Florquist	Andy O'Malia	Kliess Brown
M. H.Collett	Ray Boyd	Frank Hawksworth[2]	Roy Hanson[3]		Dwight Hester
Harry Brown	Carl Edminster[2]	John Schmid[2]	Roger Kerbs[3]		Lee Ross
Charles Con-naughton	Francis Herman	Charley Wallmo	Manuel Martinez[2,3]		Ralph Read
Willie Curtis	Bill Hornibrook		Steve Mata[2]		"Steve" Stevens
Jerry Dunford[1]	John Jones		Don Moore		Hugo Werner (Chief of Party)
Ernie Frank	Ed Kotok		Stu Parks[3]		
Howard Gary	Bert Lexen[1]		Don Reichert[2]		
Bert Goodell[1]	Sue McElderry		Slim Smith		
Arden Haeffner	Todd Mowrer[2]		Dan Taussig		
Burchard Heede	Dan Noble		Ross Watkins[2]		
Marvin Hoover[1]	Frank Ronco		George Wheatley[3]		
Paul Ingebo	Wayne Shepperd[2]				
Merrill Kaufmann[2]	Joye Smith				
Chuck Leaf[1]	Rudy Stahelin				
Grenville Lloyd	Ray Taylor[1]				
Dud Love[1]					
Pete Martinelli					
Jim Meiman[2]					
C. H. Niederhof					
John Retzer[1]					
Bob Swanson					
Butch Skow					
Jess Thompson					
Chuck Troendle[2]					
Hal Wilm[1]					

[1]At one time, responsible for overall management and research direction of FEF.

[2]Active 1987.

[3]Technician in charge of operations.

The Role of Experimental Forests in Forestry Research

John M. Ohman, Charles M. Loveless, Richard G. Cline, and M. Dean Knighton[1]

When the pioneers reached Ohio in their march to settle the interior, they found a hardwood forest so dense that it is said a squirrel could scramble through the treetops all the way from Lake Erie to the Ohio River. Clearing that land for agriculture was a monumental task, but one made more palatable by the growing Nation's demand for timber. In the early years of our country, the wood supply must have appeared limitless. But by 1831, the fledgling Federal Government acknowledged that was not the case: Congress passed a law specifying punishment for cutting, destroying, or removing live-oak and other timber or trees. But passage of this legislation demonstrates that America's politicians recognized our timber resources were finite.

By the end of the Civil War, the prospect of a timber famine--or at the very least, a shortfall in meeting America's expansionist appetite for wood and wood products--provoked Congress into action once again. A rider attached to the 1876 general appropriations act designated that $2,000 be used to investigate, among other things, the wood-supply outlook for the future, the best means for preservation and renewal of the Nation's forests, and the effects that forests have on climate. USDA's Division of Forestry was formed in 1886, and this organization, in turn, was the precursor of the Research Branch of the Forest Service.

Under the direction of division chief B. E. Fernow, a professional forester, the original "investigations" became more technical and broadened in scope to involve extension activities--possibly America's first technology transfer effort!

Gifford Pinchot took over the division in 1898. The forest reserves, which had been set up in the Department of the Interior, were transferred to the Department of Agriculture in 1905. This event marked the birth of the Forest Service.

Many researchers worked directly for national forest administrators during this period. Though studies were designed and sample plots established, research was often begun without much advance planning. Changing personnel and the lack of adequate supervision resulted in the accumulation of incomplete data and regular loss of records. Agency priorities emphasized efforts to administer the large areas of land contained in the forest reserves (called national forests after 1907). Research was essentially subordinated to the demands of National Forest administration.

The consolidation of all Forest Service research activities in a Branch of Research, under the Chief Forester's coordination in 1915, marked a turning point toward better planning and improved quality control.

Creating the First Experimental Areas

Franklin Hough's final report in 1882 suggested that land areas specifically devoted to forestry research be set aside exclusively for that purpose. The first evaluation of such an area--the Santa Rita Reserve, just outside Tucson, Arizona--was completed in 1902. A presidential executive order allocated this area to range research in 1910, adding it to the agricultural experiment station established there a decade earlier.

The first forest experiment station, in Fort Valley, Arizona, was established in 1908. It was followed soon after by the Fremont, in Colorado, in 1909.

During this period, the classic Wagon Wheel Gap watershed study was initiated and handled as a branch of the Fremont Station. This was the only study of its kind in America, and paralleled only one other such effort, in Emmenthal, Switzerland. The lessons learned at Wagon Wheel Gap enabled scientists to refine their understanding of the techniques required for long-term watershed research

The Nation's First Experimental Forests

While America struggled through the Great Depression, Forest Service research expanded greatly. Though we had been doing research since the earliest days of the century, it was not until the McSweeney-McNary Act of 1928 that a separate research arm of the Forest Service was officially

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sanctioned. Economic conditions restricted the amount of money available, but Civilian Conservation Corps and Works Progress Administration enrollees provided the labor to expand our physical plant greatly.

The first experimental forest was officially designated on January 21, 1931. Appropriately, it was the Fort Valley Experimental Forest, site of the first forest experiment station. Of the 113 experimental forests eventually set aside, 39 were established during the thirties.

Experimental Forests Between 1930 and 1980

Increasing concern about the Dust Bowl during the thirties led to the establishment of several research watersheds now considered invaluable for their long-term records. The most notable of these were Coweeta, in North Carolina (53 years of record), Davis County, Utah (51 years of record), and San Dimas, California (49 years of record). This conference celebrates the 50th anniversary of the Fraser Experimental Forest, established in 1937 here in Colorado.

The decades of the forties and fifties saw additional experimental forests incorporated into the system, but at a much slower pace. Budget constraints and the need for site-specific research programs limited the system's rate of expansion. The environmental awareness of the 1960's resulted in another flush of experimental-forest establishments. But, interestingly, this period saw the deletion of 16 experimental forests.

Where Do the Experimental Forests Stand Now?

Experimental forests started out as independent local centers of research. They evolved into a network of areas of land dedicated to accomplishing the research objectives of the more regionally oriented forest and range experiment stations. These areas continue to be a valuable resource in our search to understand complex forest ecosystems. But the primary value of experimental forests is their availability for long-term experimental studies. They also serve as representative ecosystems from which research results can be extrapolated or compared with other geographic areas.

Long-term research records are absolutely essential in studying hydrologic cycles and the factors affecting those cycles. It takes at least 4 years--often more--to adequately calibrate a watershed. And this must be done prior to beginning experimental treatments.

The value of long-term records in silvics and other aspects of forest-management research is also obvious, given the length of the life cycle of most trees and the associated rotation length of forest stands.

Experimental forests have provided us with a place to do long-term studies without worrying about our ability to complete them because of conflicting activities (such as the need to cut timber or show a profit). Our understanding of the effects of timber management and the functioning of ecosystems has been greatly enhanced through studies on experimental forests. Long-term silvicultural studies there have produced both local and basic information directly connected to improvements in forestry practices. Typically, these studies have focused on stocking, thinning, growth and yield, and regeneration.

Experimental forests are intentionally located to be representative of the range of environments encountered on lands managed by the Forest Service. The Fraser Experimental Forest, for example, features conditions typical of a high-elevation subalpine environment.

Long-term silvicultural studies are frequently well suited to wildlife investigations, a subject of increasing interest to the Forest Service. Wildlife habitat changes because of changing conditions as forest stands grow and mature. Habitat alterations bring about sharp differences in wildlife species composition. This phenomenon was observed at the Fraser Experimental Forest in research associated with studies of timber-management practices.

Emphasizing Watershed Research

Watershed research is another area that benefits greatly from its association with experimental forests. It demands long-term data sets, both for calibration and for comparison. A few watershed studies were begun at the early forest experiment stations, and permanent watershed studies were developed at several experimental forests during the expansion period of the 1930's. The data sets established over the intervening years are considered treasured assets at these locations, forming the background against which current studies can be evaluated.

Relatively few experimental forests enjoy a continuous history of watershed data approaching 50 years. To some, emphasizing the length of continuous watershed data might sound like a numbers game. It is not. Year-to-year climatic variability makes it difficult to draw conclusions from short-term (several-year) data. It is progressively easier, and sounder, to draw conclusions as reference data sets encompass longer time periods. Therefore, watersheds with this asset are especially valuable.

New Concerns

As time passes and new issues emerge, we need different kinds of data from our research watersheds. Human health concerns have demanded that we pay more attention to the chemistry of stream and soil water. Concern for forest growth has brought about the current push to investigate nutrient cycling and sources of nutrient supply. Recently, data sets

dealing with nutrient chemistry have served an important additional function as sources of background information in acid deposition studies. While data from nutrient studies do not completely satisfy the demands of acid deposition researchers, this information and its continuity with other background data are particularly valuable.

If Forest Service research is to push forward in profitable new directions, we need to reexamine the areas of prior research that have benefited us the most. Certainly one of these is the development and maintenance of our system of experimental forests. They have provided us a place where we can exercise adequate control over our research operations without the fear of losing the fruit of our efforts after obtaining only part of the desired data. They have fostered an invaluable long-term data base that promises to become more important in the future.

Data on forest stands frequently do not encompass even one full rotation. Our data base for stands rounding out their rotations cannot help but become more complete and instructive thanks to the work done on experimental forests.

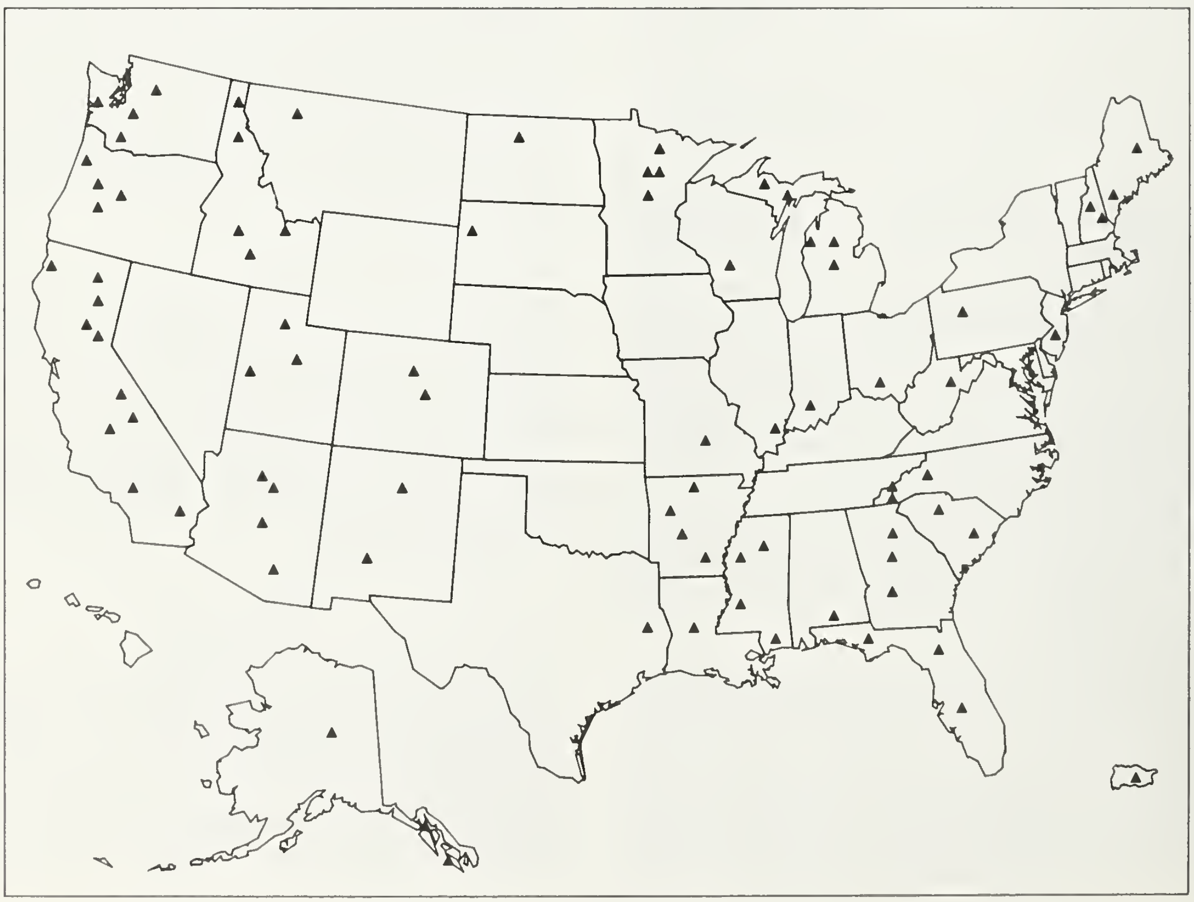
These forests have more value as a system than any single location or data set can provide. The accumulation of data over long periods of time and wide geographic areas has great potential. Our participation in the Man and the Biosphere and Long-Term Ecological Research programs is evidence of the Forest Service's commitment to the long haul. We need a system of diverse locations to achieve our research goals.

The experimental forests are furnishing large amounts of data at an astonishing rate, but the information contained in these data cannot be used until people know about it. Our challenge is to analyze and publish our results so what we have learned can be used. This is no small task. We are further challenged to make the geographic comparisons that the data accumulated from the various parts of our experimental forest system can support. Drawing conclusions from this imposing data set is a uniquely fascinating prospect and a monumental job.

Our experimental forests are in a state of flux both in terms of their numbers and the kind of work being done there. This is a healthy situation because it means we are thinking about our objectives and making decisions to direct our course.

The future will undoubtedly bring us similar challenges and changes. Our long-term records contain information that will help us attack emerging problems in areas such as cumulative effects, global climate, and forest health. Often, however, records are not complete. In places where our watershed records cover more than 50 years, we may have water chemistry data from only half this period. Some of the chemistry important in evaluating acid rain has been collected for only 8 to 10 years.

Our task is to take positive action to meet future challenges, build upon the knowledge of the past, and make the critical decisions to assure our experimental forests are as useful as possible in the future.



Silvicultural Research in Coniferous Subalpine Forests of the Central Rocky Mountains

Frederick W. Smith[1]

Abstract--Silvicultural research in the central Rocky Mountains has been influenced by the high proportion of old-growth forests, poor markets, modest growth rates and emphasis on resources other than wood production. Four areas of research have been stressed in the reglon classification, natural regeneration, reproduction methods and density control. As a result, silvicultural prescriptions can be tailored for specific site and stand conditions to achieve a variety of resource objectives.

Silvicultural problems and research in the subalpine zone of the central Rockies are related to the unique climate and forest uses in this region. The zone, which extends from 9,000 to 11,00 feet is characterized by short growing seasons, low temperatures and high radiation (Peet 1981). Tree species in the zone are limited in number. Lodgepole pine (*Pinus contorta* Dougl. ex Loud.), Engelmann spruce (*Picea englemannii* Parry ex. Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) dominate the coniferous subalpine forests, with aspen (*Populus tremuloides* Michx.) as a common deciduous associate. Productivity is low to moderate (20 to 120 $ft^3a^1y^1$) (Green and Van Hooser 1983) and regeneration can be difficult. Steep environmental gradients, largely a function of elevation, topography and soils, result in large local variation among sites. A high proportion of existing stands are unmanaged, are relatively old and may be of low vigor. Markets for wood products are poorly developed and stumpage prices are low (Long et al. 1986). Production for consumptive use, especially on public land, often emphasizes water, grazing or wildlife over wood products. Non consumptive uses, whether recreation or preservation, are important determinants of management goals throughout the region.

Silvicultural practices are commonly less intense than in other regions and management to enhance wood production is often subordinate to producing stands to meet other resource goals. Regenerating older stands is the major task facing silviculturists in the region. With low to moderate productivity and poor markets, natural regeneration is the dominant regeneration technique. Therefore, research has emphasized reproduction methods and other techniques to secure suitable natural regeneration. Intermediate operations, mainly thinning, are used to control density, spacing and composition of naturally regenerated stands.

I will review four areas of research in subalpine forests of the central Rocky Mountains dominated by Engelmann spruce and subalpine fir, or lodgepole pine classification, natural regeneration, reproduction methods and density control. These areas are of the most interest to silviculturists and have been emphasized in research programs on the Fraser Experimental Forest and throughout the region.

Classification

Classification schemes used in the Region meet two needs indexing productivity and delineating vegetative associations. Site index curves are available for Engelmann spruce (Alexander 1967) and lodgepole pine (Alexander et al. 1967). In conjunction with growth and yield simulators, they provide a means to estimate site productivity under a variety of density management regimes (Alexander and Edminster 1980, 1981). Lodgepole pine is one of the few species where dominant height is known to be reduced at high densities. Therefore, corrections factors have been developed to adjust site index estimates for density related height reduction of site trees (Alexander et al. 1967).

Habitat typing is a vegetative classification system which has recently come into wide use in the central Rockies. Methods for typing large geographic areas have been standardized (Pfister and Arno 1980), and habitat types have been

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developed for most National Forests in the region (e.g. Hoffman and Alexander 1976, 1980, 1983, Steele et al. 1983, Hess and Alexander 1986). Habitat types are defined as the land area which supports or will come to support a given climax community or plant association, and are named for the dominant or indicator species of the overstory and understory unions. Where climax vegetation does not occur, the habitat type can be identified from keys based on occurrence and abundance of seral species. A successional pattern for overstory and understory vegetation and response of different successional stages to disturbance are usually described for each habitat type.

Habitat types provide useful information for prescribing silvicultural treatments. Reproduction methods can be tailored to the pattern of ecological behavior (e.g. tolerance or successional status) of a species in specific habitat types. Regeneration problems, such as release of aggressive competing understory species, can be predicted. From descriptions of the understory union, forage production and palatability can be estimated for domestic grazing or wildlife habitat requirements.

Regeneration

Natural regeneration is the primary technique applied in the region and artificial regeneration is used only under extreme circumstances where natural regeneration has failed or is likely to fail. Successful natural regeneration depends on the provision of a sufficient supply of sound seed, and favorable conditions for germination and early survival. Successful regeneration prescriptions, especially in the relatively harsh environments common to the subalpine zone, depend on a knowledge of these relations (Alexander and Shepperd 1984, Alexander et al. 1984).

Natural regeneration of Engelmann spruce appears to be dependent on high seed production and favorable microsites. Spruce seed production may be higher and more regular than previously thought. In a 15-year study of production rates, good to excellent seed years (> 100,000 seeds per acre) occurred in 7 out of 15 years, but production varied by location and year (Alexander et al. 1986). On a stand basis, seed production was correlated with the basal area of dominant and codominant spruces. In clearcut openings, germination and survival were related to aspect and microsite. On north-facing slopes with scarified and shaded seedbeds, 25,600 sound seeds per acre were required to produce 800 5-year-old seedlings per acre (Alexander 1984). On south-facing slopes, germination and survival were poor even with the most favorable seedbed conditions (Noble and Alexander 1977, Alexander 1984). Clearcut openings that can be successfully stocked on north aspects are limited to 300 to 450 feet wide where seedbeds are scarified and shaded and 200 to 350 feet where seedbeds are scarified or shaded (Alexander 1986b). Survival is so poor on north slopes with unfavorable seedbeds and on south-facing slopes that natural regeneration of clearcut openings is not a viable option.

Regeneration of lodgepole pine requires completely different silvicultural considerations. Lodgepole pine is an aggressive pioneer and an excess of regeneration may be more common than a regeneration failure. Where serotinous cones are present, any harvesting technique which leaves the cone bearing slash distributed through the opening will provide an adequate source of seed. Regeneration in excess of 100 thousand seedlings per acre can occur following natural disturbance or harvest (Clements 1910). Where cones are predominantly nonserotinous, seed dispersal distances must be accounted for when designing openings. Mechanical scarification or broadcast burning improve microsite conditions by limiting temperature extremes and improving soil moisture availability in relation to a duff surface (Hungerford 1980, Lotan and Perry 1983). Reproduction methods and treatment of the cone-bearing slash may be modified to reduce the amount of seed available to produce lower numbers of seedlings.

Reproduction Methods

All of the high forest reproduction methods except the seed tree method are applicable to regenerate Engelmann spruce stands. Choice of an appropriate method depends on the pattern of ecological behavior of spruce in a particular stand and the management objectives for the stand. Some form of partial cutting may be required where spruce regeneration is difficult to achieve in openings, or where management objectives dictate maintenance of a mature forest canopy for an extended period.

Clearcutting in spruce is most commonly used in conjunction with natural regeneration. In the open environment of a clearcut, successful natural regeneration is more likely on a north- or east-facing slope than a south- or west-facing slope (Alexander 1984, Alexander 1986a). Size and shape of clearcuts in spruce are limited to distances that will provide adequate seed dissemination throughout the cut area. Provision of bare mineral soil seedbeds and shade for regeneration are important considerations for success in clearcuts (Alexander 1986a).

Size, shape and orientation of clearcuts are influenced by a variety of forest management objectives, especially enhancement of water yield. Water yields from spruce-fir stands can be increased by patch clearcutting. Optimum increases occur where 30% to 40% of the area within a watershed is harvested in small, 3- to 5-acre openings dispersed over the entire area (Leaf 1975, Leaf and Alexander 1975, Troendle and Leaf 1981, Troendle 1982, 1983). Differences in canopy height causes snow to be accumulated in these openings, which, in turn, increases stream flows at snowmelt in the spring. These effects decline with time as canopy height differences between an opening and the surrounding stand disappear and as

transpiration increases with accumulation of canopy leaf area. On north-facing slopes, shelterwood can be as effective as clearcutting for increasing water yield. Interception and consumptive water use are decreased while evaporation is less than in a clearcut opening (Troendle and Meiman 1984).

Patch clearcutting in successive entries is complicated by the slow height growth of Engelmann spruce. Spruce may require 20 to 40 years to reach breast height, and height of dominant trees at a total age of 60 years (breast height age 30) on SI100 80 may only be 33 feet (Herring and McMinn 1980, Alexander 1986a). Long cutting cycles are required to restrict the size of contiguous openings and to obtain stand heights necessary for adequate seed dispersal.

Partial cutting for even-aged management can be achieved with uniform or group shelterwood. A shelterwood can be applied across a wide range of site conditions but may be necessary to achieve even-aged natural regeneration on south- or east-facing slopes (Alexander 1986a). Shelterwood is used to promote natural regeneration by ameliorating site environmental conditions and providing a seed source. Also, shelterwood may be used to extend the period during which a stand meets other resource objectives by maintaining a partial mature forest canopy until regeneration is established.

Guidelines for uniform shelterwood cutting have been developed for old-growth spruce-fir stands based on stand structure, windthrow hazard and advanced regeneration, (Alexander 1986a). For single-storied stands with low windthrow risk, a three step shelterwood including a light preparatory cutting, an establishment cutting, and one or more removal cuttings after adequate restocking is recommended. For stands with higher risk for windthrow, several preparatory cuttings may be necessary to provide a windfirm stand for the establishment cutting. For stands with two or more canopy stories without a manageable understory on low windthrow risk sites, the upper story may be windfirm, and the preparatory cuttings may be unnecessary. An overstory density of 40% to 60% of the original stand basal area is recommended following the establishment cutting.

The removal cutting of a uniform shelterwood (simulated shelterwood) may be applied where sufficient advanced reproduction is present as a product of natural stand development or inadvertent response to previous cutting (Alexander 1986a). Where advanced reproduction is present, uncertainty in achieving regeneration of harsh sites can be reduced, and rotation age can be shortened. However, advanced regeneration must be of sufficient quantity, quality, species composition and uniformity in spacing to constitute a well-stocked stand. Estimates of damage to reproduction during harvest should be deducted from pre-harvest stocking to assess the adequacy of the understory for management. Pre- and post-harvest stocking evaluations and design of logging operations to control damage to reproduction are recommended.

Group shelterwood may be appropriate where mature stand structures are clumpy (Alexander 1986a). Openings less than two tree heights in diameter are cut to take advantage of the natural distribution of clumps in a stand. A stand can be regenerated in three entries by removing about 30% of the original basal area over about 1/3 of the stand area in each entry. Second and third entries can be made only after openings created in the previous entry are adequately restocked. Openings created in the final entry may require alternative means of regeneration. Openings from the final entry can be artificially regenerated, or if sufficiently windfirm to provide a reliable seed source, they can be cut as a uniform shelterwood.

Uneven-aged management can be applied in Engelmann spruce and subalpine fir stands by individual tree or group selection (Alexander 1986a). Where spruce and fir occur, they are generally climax species but may or may not be major components of seral communities (Alexander and Shepperd 1984, Alexander et al. 1984). Mature stands frequently have more than one canopy story, which can decrease the time required to achieve a balanced diameter distribution. The major difference between selection and some modifications to clearcutting and shelterwood is the way growing stock is regulated. Selection is distinguished by controlling stand structure throughout a unit on the relation of numbers of trees in successively smaller diameter classes (q), the basal area of the stand, and the maximum diameter. A q between 1.3 and 1.5 is recommended as a reasonable initial goal for regulating previously unmanaged stands (Alexander and Edminster 1977). Selection is an intensive management practice that can be difficult and expensive to apply. Alexander and Edminster (1977) have suggested marking procedures for conditions common to the region.

Normally, even-aged reproduction methods are best suited to maintain vigorous, productive lodgepole pine stands because of the intolerance of the species and the prevalence of dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) in mature stands (Alexander 1986c). However, it is possible to apply selection reproduction methods in mature old-growth pure or mixed lodgepole pine stands where management goals require minimal disturbance to the forest.

Clearcutting is the most common reproduction method applied in lodgepole pine stands because of the advanced age of many stands in the region and their susceptibility to insects, disease and windthrow. Where natural regeneration is dependent on a nonserotinous seed source, size of cutting units, logging plans, slash disposal and seedbed preparation should be designed to provide for seed dispersal, promote seedling establishment and create conditions favorable for growth. Effective wind dispersal of lodgepole seed limits clearcut size to a diameter of 300 to 400 feet, or about 5 to 6 times tree height on favorable sites (Lotan and Perry 1977). A bare mineral soil seedbed is the most favorable for regeneration, and can be created by broadcast burning or mechanical treatment in conjunction with logging or slash disposal, since seed is not contained in cone bearing slash.

Clearcut unit size is not limited by seed dispersal where cones are serotinous, but there is only one opportunity to

achieve successful natural regeneration. However, Alexander (1986c) sees no advantage to openings larger than 30 to 40 acres, even for dwarf mistletoe control, and smaller openings may be more consistent with non-timber resource objectives. Slash treatment alternatives are limited since the cone bearing slash must be preserved and distributed throughout the cutting unit (Tackle 1964, Alexander 1966). Slash treatment can be achieved by lopping and scattering or rolling and chopping. Bare mineral soil should be present on at least 40% of the area for suitable regeneration.

Partial cutting to regenerate an even-aged stand can be accomplished with uniform or group shelterwood where shade is required because of harsh site conditions or where management goals dictate extension of the time a mature canopy is present on the site. In group shelterwood small openings are created and regenerated in a sequence so that the regeneration in the entire stand can be treated as an even-aged management unit. Recommendations for uniform and group shelterwood are based on stand structure, windthrow risk, and insect and disease problems (Alexander 1986c). Repeated entries are recommended at five to ten year intervals or when current openings are adequately stocked. In uniform, single-storied, low windfall risk situations, a stand can be completely regenerated in 2 cutting cycles with uniform shelterwood and 3 to 4 cycles with group shelterwood. As windfall risk increases, the basal area or unit area cut in one entry decreases, and the number of cutting cycles required to completely regenerate a stand increases.

Thinning

Thinning represents the most powerful silvicultural tool available to shape the structure of naturally regenerated stands of lodgepole pine, or Engelmann spruce and subalpine fir. Precommercial thinning can be used to shorten rotations, to create economically viable management regimes, to improve stand composition, and to improve stand vigor and value, and resistance to insect attack (Long et al. 1986). Recent evidence suggests that susceptibility to mountain pine beetle attack (Berryman 1982) and defoliators such as the spruce budworm (Cates et al. 1983) is related to reduced stand vigor. Precommercial and commercial thinning can maintain high individual growth rates to maintain high stand vigor. Thinning to reduce canopy leaf area and transpiration may be effective in increasing water yield from subalpine forests (Knight et al. 1985, Troendle 1987). Habitat for various wildlife species may be improved by thinning (Crouch 1986). Ungulate hiding cover guidelines are most effectively met by sapling stands precommercially thinned to forestall the age of self-pruning of tree crowns (Smith and Long 1987).

Quantitative models are available to test the results of thinning regimes for volume production and stand structural development. Growth and yield simulation models include RMYLD, a whole stand model for even-aged and two-storied stands (Edminster 1978), and PROGNOSIS, an individual tree model, for even and uneven-aged stands (Stage 1973). Treatment effects on stand volume, tree size, and disease or insect infestations can be simulated with these models. Density management diagrams (McCarter and Long 1986) and stocking charts are useful tools for devising sound density management prescriptions to achieve specific resource goals. Increasingly, growth projection systems are being linked with production models for non timber resources. For example, stand structures meeting ungulate thermal and hiding cover guidelines are displayed on density management diagrams (Smith and Long 1987) and a hiding cover simulator is directly linked to PROGNOSIS.

Conclusions

Silviculturists have the knowledge base to prescribe stand level treatments to meet management goals specific to regional conditions as the result of the accumulated research on the Fraser Experimental Forest and throughout the region. Classification systems provide the means to characterize site specific problems and opportunities for production of various resources. Relations describing seed production and dissemination, and seedling survival with respect to microsite and topographic conditions have been generally described for natural regeneration. Guidelines are available to prescribe reproduction methods for old-growth stands of lodgepole pine, and Engelmann spruce and subalpine fir in relation to stand structure, windthrow risk and management goals. An array of quantitative tools, including simulation models and applied density management guides, are available for use in evaluating stand specific density management alternatives.

Further research in the central Rockies should proceed in two directions--developing cost effective, site-specific techniques for devising stand level prescriptions, and developing stand and landscape scale relations between stand structures and nontimber resources. More precise techniques to characterize site environmental variation are needed. Incorporation of topographic and soil influences on site may improve the resolution of classification systems (e.g. Peet 1981). Clarification of site-specific relations for seedling establishment will allow silviculturists to more closely tailor regeneration prescriptions to stand conditions. Development of techniques for less intensive applications of selection would allow more uneven-aged management practices in the region. Quantification of early growth rates and stocking relations of managed stands will lead to clearer choices for early density control to achieve desired stand structures.

Design of prescriptions to meet multiple use objectives will become increasingly important in the central Rocky Mountains. Ways to integrate individual stand prescriptions to produce desired conditions on a variety of landscape scales are needed. This will include of better understanding of the relation between specific stand structures and other compo-

nents of subalpine forests such as wildlife habitat requirements, water yield, sediment production, scenic values and recreational use.

Acknowledgement

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245 # Practicality of Applying Silvicultural Research on Subalpine Conifer Forest

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Abstract--Silvicultural research has provided the tools that are routinely used by the practicing forester. There are many outside factors such as social, economic, political, and agency policy that affect the application of "state of the art" silvicultural practices.

Forest Types

The forest types that make up the subalpine conifer forests are lodgepole pine, (SAF forest cover type 218) and Engelmann spruce-subalpine fir (SAF forest cover type 206).

Lodgepole pine occupies 13 million acres in the Rocky Mountain and Pacific Coast areas. It is one of the most wide spread species in the western United States. In the Rocky Mountain area it grows at elevations of 6,000 to 11,500 feet where snow ranges from 120-250 inches per year (Alexander et. al. 1983).

Engelmann spruce-subalpine fir occupies 10 million acres in the western United States. In the Rocky Mountain states south of Idaho and Montana it occupies sites that range in elevation from 9,500 to 12,000 feet. It is the forest type that occupies the highest, wettest, and coldest forested continental climate in the western United States. Snowfall ranges from 150-400 + inches per year with temperatures that range from -50 to above 90° F (Alexander and Engelby 1983).

What Has Research Given Us?

Research has given the practicing forester biological information about the subalpine conifer forest that is necessary to manage the forest: items such as species longevity, shade tolerance, wind firmness, seed and seeding characteristics, site indexes and associated growth rates, site requirements and range, insect and disease susceptibility, as well as relationships with other plants and animals.

Even-aged and uneven-aged silvicultural systems have been examined and the responses of the subalpine conifer species to these systems have been documented.

Computer models have been developed to help the field forester evaluate management objective benefits, and timing and intensity of various silvicultural practices during the planning process. This allows the forester to take a look in a matter of minutes at the results of a variety of prescriptions that would take decades to evaluate if applied on the ground. Models that predict water yield and wood fiber yield have been developed and improved over the years.

Through past research various tables that the field forester takes for granted were developed. There are tables on volume, growing stock levels, site indexes and more. Rating systems for insect and disease susceptibility and severity, such as the dwarf mistletoe rating system and stand susceptibility to mountain pine beetle, have been developed.

Guidelines have been published to guide the practitioner in planting, thinning, harvesting, seed bed preparation, protection, and more.

Most early silvicultural research was done with the objective of timber management in mind. As societal values started to change, research was initiated for objectives such as water, range, visual quality, wildlife, and recreation. Even today most publications that deal with non-timber values talk about the trade-off of timber values that are necessary to implement those practices.

How Do Forest Managers Use Research Information?

Ideal

The field forester examines the forest land to determine what the existing stand characteristics and conditions are. The forester then determines what the land management objectives are for the land, combines that information with "state of the art" silvicultural knowledge and tools that have been provided by the researchers, and writes the ultimate management prescription for each stand. These prescriptions are then implemented on the ground with all appropriate records kept and filed. The forester and the forest live happily ever after--at least until the next rotation of the forest, or the forester.

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Reality

Foresters are applying "state of the art" silviculture with varying degrees of success. Success depends on many things such as land ownership and associated land management objectives, resource agency policies, societal values, politics, and the value of forest products.

Land Ownership and Associated Management Objectives

Forest land ownership can be divided into federal, state and local government, and private land. Lands owned by various governments remain in continuous ownership more so than private land. The best opportunity for applying "state of the art" silviculture is on those lands that remain in continuous ownership and are not designated as "multiple-use" lands.

Forest land management objectives vary greatly, but generally include one or more of wood fiber, water, forage, or wildlife production; recreation, healthy forest, or preservation.

Private Lands

On private land, the landowner is the only public that the forester must satisfy, except in locations where state or local forest practice acts restrict or require certain activities. The landowner sets and prioritizes the objectives for forest land management. The practicing forester can take those objectives, along with the forest stand condition, and combine them with "state of the art" silviculture to make specific prescriptions. These prescriptions are then implemented according to the landowner's time schedule.

In Colorado, most private forest land owners do not manage their forest lands for wood fiber production. Rather, they are primarily interested in maintaining a "healthy forest." Wildlife, fuel reduction, improved grazing, and forest products are secondary. Private land provides an opportunity for truly multiple use of forest lands, but it is the landowner who makes the final decision on what conflicting prescriptions have priority.

The landowners are generally willing to manage their forest lands as long as it does not cost them anything or they can realize a return of a few dollars. A few landowners are interested in recovering the value of the forest products on their land.

As long as the land base remains in the same ownership the stated management objectives are valid, thus the silvicultural practices are appropriate and will be completed over time. When ownership of forest land changes, chances are that the land management objectives will also change. Thus the recommended long-term silvicultural practices may not be completed. Small private forest ownerships make some of the silvicultural practices impractical. Practices which make a significant change in the existing forest cover are not likely to be implemented on small acreages even though the long-term objectives of the landowner would be met.

State and Local Government Lands

Most state and local government lands do not change ownership and are managed for objectives on a continuing basis. Management objectives may be multiple use in nature, but usually have a primary objective that is not disputed.

For example, lands owned by the Division of Wildlife are managed primarily for wildlife habitat. Any work done will be for the enhancement of wildlife. Benefits to other resources are incidental. Land owned by the City of Colorado Springs for watershed is managed for the protection of water quality and water yield. Other benefits are recreation, wildlife habitat, and forest products as long as they do not detract from water objectives.

Silvicultural prescriptions that are made for these primary objectives stand a good chance of being implemented over the long term. There is less chance that these objectives will be disputed and changed during the rotation.

Federal Lands

Within the federal ownership there are lands that are designated as multiple-use lands such as Bureau of Land Management and the National Forest lands. Other lands such as National Parks and Wildlife Refuges are single-use lands.

Single-use lands, similar to those of State and local government, stand a good chance of seeing silvicultural prescriptions completed.

On multiple-use lands the public has a say in the land use allocation process and the prescriptions that are made. It appears to me that no special interest groups, whether they are preservation oriented groups, grazing associations, timber associations, four-wheel-drive clubs, skiing enthusiasts, fishing and hunting groups, mineral interests, water users or any of the numerous groups, are willing to settle for their "piece of the land use allocation pie." The constant jockeying for position to try to get more land for their use hinders the forester from applying any long-term silvicultural practices on the ground.

Societal Values

This great country that we live in was built on the use, and yes, abuse of our natural resources. The attitude was that the resources would never end. There was always more resource over the next hill.

A large portion of the society that built this country was agriculture based. They were used to the rotation of preparing the site, planting, cultivating, harvesting of crops, and starting over again. Harvesting of the forest was natural to this society.

As agriculture became more efficient it took less people to feed and house the people of the Nation. This started the move from the rural to the urban areas. As the generations passed, those who lived in the country and were familiar with the agricultural process of site preparation, planting, cultivating and harvesting also passed.

The urban population, along with the rural segment of society, became more affluent and started turning to the forests for recreation. These people started to question practices such as clearcutting large blocks of forest that did not regenerate. They also questioned the practices of logger's choice, diameter limit cuts, utilization and slash disposal requirements that were the standard of the day.

These practices are often referred to as "low-intensity management" but in reality it would be more appropriate to say "No Management." The bottom line was that the forest resources were being mined.

We, as foresters, and the forest industry of the time, were using the same philosophy that was used during the expansion of the country. By using "low-intensity management," we as professional foresters lost the trust of the public as competent resource managers, and the ability to apply "state of the art" silviculture.

This was the setting that started the great public debate over how the public lands designated as "multiple-use" are in fact used. The debate not only pits preservation against consumptive use, it also divides the various types of use. For example there is conflict between the motorized recreationist and the non-motorized recreationist. The non-motorized recreationists are split between the mechanical (mountain bike) and the non-mechanical user. The non-mechanical users are split between the hiker and the horse rider.

Political

The same society that started questioning practices being used to manage the forest resources are the ones that are electing the politicians who govern the states and the Nation. This urban society provides the majority of the legislators and the powerful constituency behind them.

Legislators pass statutes to provide for input by their publics into the land management process, and they control the purse strings that ultimately control the application, or lack of application, of silvicultural practices as well as research.

Resource Agencies Policy

The natural resource management agencies are caught in the middle. They have the charge of managing the resources they have been entrusted with in a manner that will provide a sustained yield of multiple-use outputs for the public good.

Regulations are promulgated to implement the various statutes. To provide an opportunity for the public to be involved in the land management process, we provide for public hearings, and an administrative appeal process. Plans are prepared for a 50-year period with revisions every 10 years, and the possibility of amendments at any time.

The various publics that are jockeying for a larger piece of the land allocation pie have learned to use the appeal process very well. To prevent the agencies from implementing a management program they don't agree with, they can appeal the plan, or an individual project, for the cost of a postage stamp. The appeal process is used extensively as a delaying action.

If action can be delayed long enough they will have another shot at changing the land use allocation, thus the land management objectives, in the next planning period. How can the practicing foresters realistically implement silvicultural prescriptions that may take 40 or more years to complete when the objectives may change within 10 years?

In the process of negotiating a compromise with appealing special-interest groups, changes are made to prescriptions to make them acceptable. These changes may become standard over a period of time and add cost to the project.

Since many resource management objectives are implemented via the timber sales program, these additional costs make the sales appraise out at deficit, and they will probably end up being "below-cost sales." Many of these sales will not be sold because the forest products industry can not make a profit. The opponents of timber sales, and some agency managers, say the industry does not need or want the timber so they should reduce the volume offered. A vacillating and undependable supply of raw material makes the viability of the forest products business even more questionable.

Practicing foresters need to work with the timber industry in a partnership role. We have to have industry in order to complete the majority of our work. We have to realize that industry is not in business for the fun of it, or to do what is good for the forest, but is solely profit motivated.

Resource management agencies get caught up in their own bureaucracy. We are trying to be all things to all people. We want to be sure that we are responsive to our publics, and also be sure that we do everything exactly right, (to the point that we spend most of our time playing "CYA.") Professional foresters are involved in the planning process, writing environmental impact statements, taking additional training (so that we can become certified to do our job such as write management prescriptions, cruise forest stands, and scale logs), preparing budgets etc. These are necessary tasks, but with all of this there is little time to get out in the field to DO the job!

We end up hiring seasonal workers, who may be forestry students at best, to do the "on the ground" work. The best-written silvicultural prescription, if not applied correctly on the ground, will not be acceptable to our "publics" let alone ourselves. Professional foresters should be the people on the ground applying the prescriptions.

Resource management agencies have started using specialists to do various aspects of the job. One person cruises the stand, another writes the silvicultural prescription, another lays out the prescription on the ground, another designates

access roads, another writes the contract, another administers the contract, and yet another evaluates the job. Chances are that the people who initiated the project have been transferred to another job and may never see the results of what they did. No one has ownership of the job, nor has anyone learned from his own mistakes.

Other Factors

Water Law

In Colorado the water rights are allocated by law on a seniority basis. In most cases a landowner, whether private, state, or federal, does not have the right to any additional water that results from silvicultural practices. "New" water is not available to the landowner to use as a salable or usable commodity, thus there is no incentive to implement water augmentation projects.

The senior water users will get their water regardless of flow, except in drought years when the water is not there. The junior users are the ones that would probably benefit the most by water augmentation, but are reluctant to pay for water augmentation work when there is no guarantee that they will get their full allotment of water.

Road Costs

Implementation of silvicultural prescriptions, other than do nothing, requires access to the area and the stands that will be treated. Size, dispersion, and shape of treatment units will determine the amount of road required.

Research has shown that there are optimum size units for different management objectives, and species response. For example, when patches of five to eight acres are used as opposed to blocks of 40 acres, the amount of road needed to access a 30% cut increases by 250%. If these costs are to be absorbed by the timber program it become impractical for industry to operate.

Funding Levels

There are many reasons that could be discussed as to why funding is inadequate to allow full application of silvicultural practices. At this point it is sufficient to say that appropriations are not keeping pace with the cost of management for most forest resource values.

Forest managers are trying to use the timber program to implement watershed management, wildlife habitat, insect and disease protection, range, recreation programs, etc. Small cuts, additional roads, multiple entries, extensive slash treatment, and limiting entry time all add to the cost of the job. To make these modifications of a silvicultural prescription to accommodate other values adds costs which can make a break even, or marginally profitable, project lose money.

Markets and Product Value

Although the value of forest products from the subalpine conifer forests is greater than other forest types in the immediate area, it is of less value than forest products from other regions. Due to the comparative lower value of the products, the demand for products from native lumber is lower.

Combining low-valued products with the increased cost of non-timber value requirements makes the practicality of applying "state of the art" silviculture primarily through a timber sale program questionable at best.

So Why Do Anything?

I believe the public will allow and support intensive forest management as long as it realizes the value of silvicultural practices. The public requires clean harvesting that has high utilization and slash treatment standards which meet the regeneration needs of the species on land that has been allocated for treatment. We will need to increase the productivity of available lands by ensuring rapid regeneration and controlling stand density.

Foresters and the forest products industry must work together as partners to accomplish silvicultural prescriptions that are feasible. Industry must realize the constraints that are placed on the field forester as well as the type and quality of forest products that are available. Foresters have to quit asking industry to do jobs that will not pay for themselves in product value.

Research has provided "state of the art" tools for the practicing forester to use on the ground. We must use every opportunity for the researcher and the practicing forester to exchange problems and research findings. Conferences like this are a good start; but need to be more frequent, include industry and other interest group representation. Publications need to be written for the practicing forester--not other research scientists.

Management agencies must be on constant guard against practices that limit their forester's ability to apply "state of the art" silviculture.

All of us (researchers, field foresters, and industry) must work together to explain to the public "what, why, where, when, and how" silvicultural practices are beneficial to the forests.

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Silviculture Research in Rocky Mountain Aspen

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Abstract.--Recent intensification of aspen management in the central Rocky Mountains has resulted in the establishment of a silviculture research program to meet management needs. A brief history of management and past research in western aspen precedes a discussion of the results and management implications of several current silviculture studies.

Management practices for aspen (*Populus tremuloides* Michx.) forests in the central and southern Rocky Mountains have not evolved in the same manner as those for conifer forests in this region. Historically, low demand for aspen wood products resulted in little interest in intensive management or silviculture research.

However, this situation has recently changed. Demand for aspen fiber and for other resource uses has intensified aspen management in the Rockies, and created a need for additional silviculture research.

The objectives of this paper are threefold: (1) review the sequence of events that led to the current interest in aspen management, (2) briefly review the principal contributions to the silvicultural information base for western aspen, and (3) discuss current aspen silviculture research at the Rocky Mountain Forest and Range Experiment Station and summarize what we are learning.

History of Management

Aspen management within the Rocky Mountain Region has increased dramatically within the last 10 to 15 years. Before this, aspen was managed only where local commercial markets existed for aspen products, such as match splints, excelsior, paneling, sawn shakes, mine props, pallets, fence poles, and other specialty products (Koepke 1976). In most cases, only large trees free of internal defect could be used for these products, which further limited the types of stands that could be commercially managed.

Prior to 1976, aspen accounted for only 2% of the annual timber harvest in the Rocky Mountain Region (Mathiason 1976), even though aspen occupies about one-third of the forested area in Colorado alone.

Two events in 1976 marked a turning point for aspen management in the Rockies. First, an awareness of the significance of the aspen resource in the Rocky Mountain Region was reflected by an aspen utilization symposium held in Fort Collins, Colo. (USDA Forest Service 1976). Participants emphasized the unique utilization characteristics of aspen and advocated more active management of the resource. The second event was the creation of an Aspen Task Force panel by the U.S. Forest Service to examine the aspen resource in the Rocky Mountain Region. This panel submitted a draft in-house report to the Regional Forester, which also called for more active management of the aspen resource and recommended that manageable aspen stands be moved to the Commercial Forest Component in the Forest Service bookkeeping system, giving them the same management status as conifer forests.

Concurrently, managers were concerned that many aspen forests were reaching maturity and soon would be replaced by conifers at the expense of wildlife habitat and scenic vistas. In 1978, yearly aspen harvesting targets to regenerate critical aspen wildlife habitat were established in Rocky Mountain Region forests. These targets were ambitious, considering the nearly 3 million acres of aspen that eventually would have to be regenerated. Their establishment did, however, set the gears of management in motion.

In 1983, the aspen management picture changed abruptly when Louisiana Pacific announced construction of two flakeboard mills in Colorado that would utilize aspen. This market for aspen could provide a means to effectively and economically manage a much greater portion of the aspen resource.

However, managers were not fully prepared for such a sudden turn of events. The flakeboard mills had not begun operation before a controversy arose over the planning process and management guidelines used by the Forest Service to

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select aspen stands for harvest. In response to litigation brought about by the State of Colorado and a coalition of environmental groups, a panel of experts representing the principal interest groups was formed in 1984 to draft management guidelines for aspen that would be acceptable to all. The results of that effort were adopted by the Regional Forester in 1985 and are in use in the Rocky Mountain Region today (USDA Forest Service 1985).

Early Silviculture Research in Aspen

The history of aspen research in the West parallels that of aspen management. The current program at the Rocky Mountain Station is an expansion of the earlier, limited efforts throughout the West.

The most important early work in western aspen was that of Baker (1918a, 1918b, 1925). His work included descriptions of aspen growth and regeneration characteristics, development of volume tables and site index classes, and regeneration observations. Baker's studies generated much of the information available until the mid-1970s, and many of his observations and conclusions are being upheld by the more quantitative work being done today.

Arthur Sampson (1919) described aspen root suckering that occurred after complete clearfelling. He observed variable regeneration success, and noted browsing and disease problems in his Utah study areas. We are quantifying some of these same regeneration problems in our research today.

More recently, aspen research was conducted by the U.S. Forest Service at both the Rocky Mountain and Intermountain Forest and Range Experiment Stations. Two people were responsible for much of the early work in aspen at the Rocky Mountain Station.

Tom Hinds produced much of the available literature on aspen canker diseases in the West (Hinds 1964, Hinds and Krebill 1975) and their impact on aspen fiber resources (Hinds and Wengert 1977). Although retired, he remains an active cooperator on current silviculture studies.

John Jones initiated silviculture research in aspen at the Rocky Mountain Station in the mid-1960s when he published site index curves for aspen and a series of ecological and regeneration studies (Jones 1966, 1971, 1974, 1976; Jones and Trujillo 1975a, 1975b). This material served as the basis for the first draft of a book later revised and published as General Technical Report RM-119, "**Aspen: Ecology and Management in the western United States**" (DeByle and Winokur 1985).

Aspen research at the Intermountain Station was more involved. A research work unit entirely devoted to aspen was maintained by the Intermountain Station from the early 1970s until 1985. Research by Walt Mueggler, Norbert Debyle, George Schier, Dale Bartos, Bob Campbell and others greatly expanded our knowledge of the physiology, regeneration, ecology, and wildlife habitat relationships of western aspen. The numerous contributions of these researchers are summarized in Debyle and Winokur (1985).

Current Silviculture Research at the Rocky Mountain Station

Current aspen silviculture research at the Rocky Mountain Station emphasizes aspen stands that have the potential for commercial management. This research developed in response to the need for more information about how the large aspen resource in the Rockies should be managed.

Our aspen growth and yield research has included the development of volume tables (Edminster et. al. 1981, Shepperd and Mowrer 1984), site index curves (Edminster et. al. 1985), an aspen module for the RMYLD stand growth model (Edminster and Mowrer 1985), and a normal diameter distribution growth and yield model (Mowrer 1986). We also have produced equations for estimating bark thickness and past diameters (Mowrer and Edminster 1985), mean annual volume productivity (Mowrer 1986), and leaf areas (Kaufmann et. al. 1982).

We currently have several studies of growth, regeneration, and cultural activities underway in aspen. I would like to briefly share some preliminary results and observations from these studies.

The Aspen Stand Classification Study (Shepperd 1981) has been underway since 1979. This study was undertaken to meet two objectives: (1) describe the range of stand and growth conditions occurring in aspen in the central and southern Rockies, and (2) develop a classification system based on information available from Stage II inventory that would be helpful in making management decisions in existing stands.

Growth, site, and clonal characteristics from 140 aspen stands throughout Colorado and southern Wyoming were compared. A number of trends were noted (Shepperd 1981).

1. Most aspen in the Rockies is mature, from 60 to 120 years old. Younger stands are rare, but occasional old-growth (120-180 years) stands can be found.
2. Not all aspen is even-aged. About 20% of the stands encountered were two- or multi-aged.
3. Aspen grows on a variety of sites in association with both montane and subalpine vegetation.
4. Growth characteristics expressed on a clonal basis can be useful in identifying stand condition. For instance, height of live branches can be used to identify the relative age of a stand, and yellowish bark color may be indicative of stress.

A cluster analysis is being used to incorporate these and other relationships into a classification scheme based on stems per acre, average stand age, average stand height, and site index. These characteristics have been used to assign stands into one of seven preliminary classes that require different silvicultural or management considerations. Briefly, these classes are:

1. Mature, average stocking and productivity. Capable of commercial management.

2. Middle-aged, poorly stocked, low productivity. Commonly occur on dry sites. May be hard to regenerate.

3. Young, dense, fast growing sapling stands without measurable commercial volumes.

4. Young, moderately stocked, sapling stands with measurable commercial volume.

5. Mature, heavily stocked, highly productive stands. Highly suited for sustained fiber production.

6. Middle-aged, healthy, well-stocked stands with high production. Management can be deferred in these stands.

7. Very old, well-stocked stands that provide valuable wildlife habitat and aesthetic appeal.

An interactive computer program also is being developed that will be able to assign any inventoried aspen stand to one of these classes and provide a narrative of suggested management alternatives. The program will enable local managers to quickly gain an understanding of how aspen stands in a local area compare to those elsewhere in the Rockies, and to identify stands requiring special silvicultural consideration.

Another of our studies that has been underway for the past 5 years is a comparison of bulldozer pushing and chainsaw felling regeneration methods in aspen. This study was undertaken on the Yampa District of the Routt National Forest to investigate more cost-effective methods of regenerating noncommercial aspen stands. The effects of fencing to exclude domestic livestock and leaving slash on site also were investigated in this replicated split-block study.

Although sucker regeneration was quite variable, several trends were apparent. After five growing seasons, dozer-pushed areas contained more suckers than those cleared by chainsaw felling. Removing the stumps apparently stimulated the remaining lateral roots to sucker more vigorously. Fenced areas appeared to contain more suckers than unfenced areas, regardless of the regeneration technique used. Leaving slash in place may have offered some protection from animals, but did not allow as many suckers to become established and, therefore, may have been detrimental.

Bulldozer pushing, if properly applied, may be a successful regeneration technique in Rocky Mountain aspen. However, the large variation in sucker counts between replications in this study indicates that site and clonal differences also might affect aspen regeneration success, regardless of the technique used.

No silviculture research program would be complete with out a thinning study. We have two underway in aspen. The first is on the Fraser Experimental Forest and is investigating the effect of a simulated commercial thinning in pole-sized, mid-aged aspen. A 1981 thinning removed 0%, 25%, 50%, and 100% of the original basal area from study areas in this stand. One posttreatment overstory growth measurement has been made, and a series of stem condition inventories have documented damage and disease progression in order to assess the effect of thinning on both growth and stand vigor. Some growth increases due to thinning may have occurred; however, mortality caused directly or indirectly by the thinning activity appears to have offset much of this growth.

Suckering response following thinning also is being monitored on permanent regeneration plots. To determine any effect of large ungulates, one-half of each thinning treatment has been fenced to exclude such animals. To date, suckering has been poor, even in the clearcut-fenced area.

The second thinning study has been installed in young aspen stands on the Routt, Gunnison, and Uncompahgre National Forests to investigate the long-term effects of early precommercial thinning. This study also will provide growth information for yield model updates. No posttreatment data have been collected, but growth increases and new suckering are both evident in some areas. Heavy snow has damaged the thinned treatments at one study site, and is another factor that should be considered before thinning young aspen in the Rockies.

Experience with these studies and data from the Routt and San Juan National Forests published by Crouch (1981, 1983, 1986) indicate that not all aspen stands regenerate well following clearcutting. This prompted us to complete a Region-wide survey of regenerated aspen stands in 1985. This survey sampled 32 areas that had been clearcut at least 5 years previously. Stocking, internal and external damage, and disease were all assessed.

Most aspen suckers were found to have some type of damage or defect. The effects of damage on sucker vigor appear to be additive. With the exception of disease outbreaks, stands appear to successfully regenerate where initial suckering is prolific and suckers are not damaged repeatedly or by multiple agents. Relationships between sucker establishment, site conditions, and preexisting stand characteristics will be investigated in future research.

The Rocky Mountain Station recently sponsored a cooperative study with Colorado State University on the persistence of isolated aspen clones. Several size and age classes were found in each of the isolated clones that were examined, but age classes were not evenly distributed throughout the clones. The investigators proposed that nonforest areas surrounding isolated clones may be colonized when a group of young suckers persists on the periphery of the clone.[2] The rates and directions of clonal expansion observed in this study were quite variable, and may not be related to stand or physiographic characteristics.

Future Research Needs

Although we have gained a better understanding of the management of aspen in the Rocky Mountains, many unan-

[2]Smith, Frederick W. and Kirk Apt. 1987. Persistence of isolated *Populus tremuloides* Michx. clones in the central Rocky Mountains. Unpublished report on file, Rocky Mountain Forest and Range Experiment Station.

swered questions remain. More aspen is now being harvested annually in the Rockies than ever before. Not all of these harvested acres are regenerating well. Understanding this variation in regeneration following clearcutting is of primary importance.

More information is needed on the condition, density, and development of the lateral root systems of mature aspen stands. We need to know how lateral root systems change as new stands develop following the harvest, as well as how the harvesting practices themselves affect lateral root system development. For instance, aerial and ground reconnaissance has shown poor stocking on skid trails and landings in some areas. We need to know whether these nonstocked areas are due to soil compaction or root system disturbance, and what conditions contribute to it.

Additional silviculture research also is needed in mixed aspen-conifer stand types. These stands offer a great deal of diversity, and provide quality habitat for many wildlife species. Such stands have traditionally been considered seral to conifers; however, evidence suggests that some of these stands have existed in a mixed overstory mode for some time. Understanding the dynamics of these stands could lead to the development of cultural practices to either maintain or perhaps establish a mixed species condition. Such techniques would not only benefit wildlife, but visual, timber, and watershed resources as well.

In conclusion, although aspen has only recently joined the ranks of intensively managed species in the central and southern Rockies, current management practice has benefited from an ongoing silviculture research program. Future management of the subalpine forest ecosystem will build upon this research base to maintain and enhance our unique aspen resource.

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245 Case Studies in the Application of Aspen Research

Robert T. Beeson[1]

Abstract--This paper examines current conditions, issues and concerns in Rocky Mountain aspen management from the land manager's viewpoint. The application of research is identified and suggested areas for targeting new research identified. The public's concern for aspen treatment is analyzed.

There are 3.5 million acres of aspen timberland in Colorado; 850,000 of these acres are on State and private lands. Prior to installation of the two waferwood plants, the annual harvest was in the neighborhood of 45,500 tons per year. This has increased to 250,000 tons. Several issues and concerns have arisen during the past few years as a result of this increase which will be discussed in this paper. Current application of research and silvicultural conflicts also will be identified.

Historical Perspective

The visual values of aspen have long been recognized as contributing significantly to the State's and Region's economy. The tree is more well known than blue spruce, Colorado's State tree or any other species. A major ski area is named after the tree. It is known by several names. To most ranchers it is a quakie. To people from Minnesota it may be popple. To several species of wildlife it is known as food or shelter. To foresters it used to be known as a weed and now is considered a fast growing public relations problem. The primary silvicultural problem is regeneration--too much of it and in a few cases not enough. Regulation of quantity and quality of these stems is of primary concern to ranchers as well.

Significant effort has been made to involve the public in planning for management of aspen but to date, a large percentage of the production of the two waferwood plants has been harvested from private and State lands because of continuing public concern and appeals of timber sales and forest plans. The management implications of this level of harvest from relatively small ownerships is a concern both to industry and service foresters.

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Current Issues

The foresters' concerns are the advanced age of the majority of this unregulated acreage and the possible succession to coniferous species. Given the current market, foresters have responded to these concerns by attempting to develop timber sales programs that greatly expand aspen regeneration programs.

Because of public concern, management programs on public lands have not proceeded to implementation. It is estimated that eight to ten thousand acres of predominantly private lands are being annually harvested which represents one percent of the total ownership.

Sampson (1919) identified the need to protect young stands from overgrazing. He recommends moderate grazing by cattle as a means to maintain land productivity from both range and timber standpoints. From experience in stands regenerated in 1984, significant variation occurs between cutting units in the amount of damage done to sprouts. Generally at least 3,000 sprouts per acre have reached four feet heights undamaged.

From the stockman's standpoint, two concerns seem to prevail. Excessive regeneration is seen to be an impediment to access. One of the suggested ways to limit regeneration is to leave a moderate amount of slash on the ground. This practice limits access according to many ranchers. They would prefer no slash at all. The current practice of mechanical harvesting, whole tree skidding with tops piled at landings seems to be a reasonable compromise to leave enough slash to slightly limit grazing thereby allowing adequate undamaged sprouts to overtop livestock.

Then what do we do with the slash piles? These are large and more often than not, not very flammable. Attempts were made two years in a row to burn piles at Carter Mountain after adequate snowfall. The piles are still there but another attempt

will be made this year prior to snowfall. The expense of slash disposal could exceed the revenue from the sale if this next attempt is not successful. Research needs here are to identify the best method of economical slash treatment from a multiple use standpoint. This treatment should leave enough on the site to impair some grazing but still be acceptable to the stockman who must herd and gather the cattle. The method should also leave the harvest "looking good" to the public and be cost effective (not more than $20 per acre total cost).

On moist sites, there is a concern that regeneration will not occur due to the rise in the water table that occurs due to removal of aspen which is a significant water user. On fuller saturation in the spring, this could also lead to land stability problems. We have not experienced this to date, because we have not harvested on excessively wet sites, but it is very evident in some unharvested sites.

Significant acreage of mixed aspen conifer stands exist. The predominant conifer is subalpine fir, which currently has limited value as timber. In general, prescriptions call for its removal during aspen regeneration. This is usually possible if the volume is not excessive. One advantage to having conifers included in the sale is that slash piles that are mixed are more flammable. In several cutting units installed to date, conifers which were considered wind firm were left standing. This practice has produced less visual impact while allowing regeneration of more than 20,000 sprouts per acre.

No real effort has been made to relate densities of sprouts surviving grazing to this size of cutting units. Wayne Shepperd, working closely with field foresters, feels there is a size of cutting unit that is too small. The results, if very small units are installed in areas grazed by livestock or wildlife, could be destruction of regeneration. Current practice usually is to design sales with ten acre and greater cutting units. Some unregulated private land sales have very large cutting units depending on the landowners objective. I feel we should pay close attention to cutting unit size in sale design and direct research towards identifying the lower unit size threshold where regeneration becomes uncertain.

All of these concerns are irrelevant if we cannot satisfy the public concern and major issue. This issue is whether aspen will receive any silvicultural treatment at all. This public concern is rooted in the belief that harvest of a renewable resource best be left to natural agents.

Support is garnered for this belief from factual and emotional reasoning. Some facts cited are:

1. It costs more to harvest aspen than is returned to the treasury. This can be true when costs are driven up by over planning. The current regional average cost of timber sales is over half planning before a single piece of flagging is tied to a tree.

2. The age class structure is predominantly mature and over mature but nature will take care of itself. Aspen will not disappear and succeed to conifers if left alone. The fact that 20% of the stands in Wayne's study are two- or more storied is evidence that most aspen will regenerate without logging.

An emotional concern is that harvesting of aspen is actually killing a stand rather than regenerating a new one. This concern arises from a belief that forest conditions are more static in nature than they actually are and a basic mistrust of the knowledge of foresters in predicting future conditions.

Foresters have responded to public concerns with detailed public involvement processes that more often do not influence basic beliefs that underlie the voiced concern. Usually the great majority of the so called public could care less until they are directly influenced. Harvesting is okay until the particular stand or tree that I am interested in is affected. This public does not participate in the decision making process but responds negatively when they feel threatened. I personally have no answers to this situation but have found that one on one show me trips of both successes and failures are the most effective public involvement.

Case Histories

Carter Mountain

This 5,000-acre block of state land was inventoried in 1982. Three thousand acres are forested with aspen and aspen-fir mixtures. It is located twenty miles from Kremmling. The management plan calls for harvest of 115 acres per year. Three grazing leases exist at one A.U. per 5 acres. Four hundred acres were sold in 1983 to Louisiana Pacific. The average unit size is 42 acres with a range from 12 to 60 acres. Logging was mechanical (sheared and whole tree skidded). As of 1987, all units are stocked with a minimum of 18,000 aspen per acre. Grazing has left enough undamaged stems to fully stock the area. Continuing problems are the rancher's concern about access because of high sprout density and the difficulty of slash disposal. Also, one cutting unit has a high rate of infection with a disease that looks like Shepherd's crook.

AMAX

In 1984 and 1985, 140 acres of aspen were harvested under a management program. Unit size varies from 10 to 40 acres. The two small units are within 0.25 mile from meadow or sage; the larger units are 200 feet higher in elevation. Grazing has not been excluded. Approximately 200 yearlings use the 1,500-acre allotment from June to October. The smaller, lower units produced 8,000 or more first-year sprouts; but most were damaged or killed by grazing. The larger, higher units are successfully stocked with undamaged stems.

Summary

The forester is attempting to "speak for the trees" when he or she sees large acreages of over-mature stands and designs

a schedule for replacing these forests with younger, more diverse stands. The landowners, either private or the tax paying public, feel threatened by this planned change and questions why? If there is doubt in the forester, it may be expressed by an inadequate response, anger or an attempt to hide the work that is progressing. We must be sure as foresters, that we really operate from knowledge of the facts before we "speak for the trees." We must also realize that most people do not understand the connection between the natural resources they use abundantly, their own livelihood, and the economy of the community in which they live. The only new wealth is either grown from or mined from the ground. If we let the number of people whose livelihood is directly dependent on producing this wealth equal one, then those who indirectly benefit but whose livelihood depends on its continued production equals 10. This secondary group has 10 times the influence in decisions, but is the most difficult to communicate with. They are too busy to participate or feel higher priority needs.

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Growth and Yield of Subalpine Conifer Stands in the Central Rocky Mountains

Carleton B. Edminster[1]

Abstract--Potential production of managed, even-aged stands of Engelmann spruce-subalpine fir and lodgepole pine is estimated for combinations of stand density, site quality, and rotations using whole stand growth models. Volume production is maximized at relatively high stand densities. Average maximum density curves are developed as a reference level for stocking standards.

Subalpine forests of Engelmann spruce *(Picea engelmannii)*-subalpine fir *(Abies lasiocarpa)* and lodgepole pine *(Pinus contorta)* are the largest and most productive timber resource in the central Rocky Mountains (Choate 1963, Miller and Choate 1964). Management of these forests affects all resources and uses. If total cubic volume production is the primary objective, stand densities should be maintained at relatively high levels.

Control of stand density offers the greatest opportunity for increased sawtimber production, increased tree and stand growth, reduced mortality, and creation of stand structures to meet other resource objectives. Forage production and water yield are substantially increased only at much lower densities. Low to medium densities are generally required to improve developed recreational opportunities and enhance foreground esthetics.

This paper presents projections of stand growth and yield for Engelmann spruce-subalpine fir and lodgepole pine, and demonstrates methods to standardize stocking guidelines for control of stand density. Comparisons of managed stands are developed from whole stand growth models for managed even-aged stands in the central Rocky Mountains. Comparisons follow a format similar to that used by Alexander and Edminster (1980, 1981) for examining the effects of repeated thinnings at various intensities for a range of site qualities and rotation ages. Management regimes examined appear to be the most reasonable based on past analysis and the silvical characteristics of the species. Related to estimates of growth and yield are methods for providing a standardized concept of stocking. Recent results in developing reference stocking levels in the standard national format (Ernst and Knapp 1985) for major subalpine forest types are also presented.

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Development of Models

The original models for computing variable density yield tables for managed even-aged stands of spruce-fir, SPRYLD (Alexander et al. 1975), and lodgepole pine, LPMIST (Myers et al. 1971), provide the basic stand growth and yield relationships incorporated into the whole stand model, RMYLD (Edminster 1978). The whole stand, characterized by average values, is the primary model unit. RMYLD projects stand development by consecutive 10-year periods, and includes relationships to project average stand diameter, average dominant and codominant height, and number of trees per acre.

For both forest types, the relationship to estimate periodic mortality for a specific set of stand conditions is relatively weak. Separate relationships express the effects of and changes in the intensity of infestation of dwarf mistletoe *(Arceuthobium americanum* Nutt. ex Engel.) in lodgepole pine stands. Total cubic-foot and merchantable volumes per unit area are calculated with stand volume equations. Relationships to estimate changes in average stand diameter and dominant and codominant height and number of trees resulting from intermediate cuttings are developed from results of simulated thinnings and trial marking in growth prediction plots.

When the original models were developed, thinned stands were available only in lodgepole pine, and those did not adequately represent the range of stand conditions necessary to develop growth and yield relationships. Many of the temporary growth plots used for the lodgepole pine model and all of the plots used for the spruce-fir model were established in undisturbed even-aged stands chosen to approximate managed stand conditions. The plots conformed to usual requirements for uniformity of site quality, range in tree sizes, and stand density across the plot. Plots were placed in areas

without catastrophic mortality, and the models are not capable of simulating such effects. A single set of growth and mortality relationships is used in the spruce-fir model for both Engelmann spruce and subalpine fir. Data analysis verified that spruce and fir growth were similar for at least 90 to 100 years. Periodic thinnings are assumed to remove most of the fir component before stand age 90, resulting in a nearly pure spruce stand.

Stand Conditions Simulated

Yields were simulated for the following range of initial stand conditions and management controls for spruce-fir stands:

1. Average age at the initial entry is 30 years. Note that the age in the yield table is measured at breast height (b.h., 4.5 feet). A minimum of 20 years is allowed for spruce and fir trees to regenerate and grow to 4.5 feet in height. Therefore, total stand age is at least 20 years older than the age measured at b.h.
2. Diameter of the tree of average basal area is 4.5 inches at b.h.
3. Stand density is 800 trees per acre.
4. Site indexes at b.h. age 100 years are 50, 70, and 90 feet (Alexander 1967).
5. Rotation lengths are 120, 140, and 160 years, with a two-cut shelterwood regeneration cutting method.
6. Periodic thinnings from below begin at age 30 years and are repeated every 30 years. Thinnings are made to growing stock levels 40, 60, 80, 100, 120, 140, 160, and 180. Growing stock level (GSL) is defined as the residual basal area per acre when average stand diameter is 10 inches or more. Basal area retained in a stand with an average diameter of less than 10 inches is less than the designated level (Myers 1967). Initial and subsequent thinnings are made to the same GSL.
7. Minimum size for inclusion in board-foot volume determination is 8 inches d.b.h. to a 6-inch top. Volumes are determined from tables prepared by Myers and Edminster (1972). Sawtimber volume is calculated for stands with average stand d.b.h. 8 inches and larger.

Yields were simulated for the following range of initial stand conditions and management controls for lodgepole pine stands.

1. Average total age at the initial entry is 30 years.
2. Average stand diameter is 4.5 inches at b.h.
3. Stand density is 1,000 trees per acre.
4. Site indexes at age 100 years are 50, 60, 70, and 80 feet (Alexander 1966).
5. Rotation lengths are 80 and 120 years, with a clearcut regeneration cutting method.
6. Periodic thinnings from below begin at age 30 years and are repeated every 30 years. Thinnings are made to GSLs 40, 60, 80, 100, 120, 140, and 160. Initial and subsequent thinnings are made to the same GSL.
7. Minimum size for inclusion in board-foot volume determination is 6.5 inches d.b.h. to a 6-inch top. Volumes are determined from tables prepared by Myers (1964, 1969). Sawtimber volume is calculated for stands with average stand d.b.h. 7 inches and larger.
8. Stands are not infested by dwarf mistletoe.

A 30-year cutting cycle was chosen because of low stumpage values and the need for cultural operations to produce commercial volumes. Length of thinning cycles has been demonstrated to have little effect on total yields (Alexander and Edminster 1980, 1981). All volume computations are based on gross volume equations with no reduction for defect. Also, stands were assumed to be fully stockable.

Growth and Yield Results

Diameter Growth

Periodic diameter growth of spruce-fir and lodgepole pine stands is negatively correlated with stand density (as represented by stand basal area), but positively correlated with site index. On an average site (index 70) for spruce, average diameters at rotation for spruce-fir stands are 25.5 to 39.5 inches at GSL 40 for rotations of 120 to 160 years. At very high stand density (GSL 180) average diameters range from 13.5 to 22.1 inches, depending on rotation age. On an average site (index 60) for lodgepole pine, average diameters at rotation ranged from 12.7 to 18.9 inches at GSL 40 for rotations of 80 and 120, respectively. At high density (GSL 160), average diameters range from 8.2 to 10.6 inches. Diameter growth at low stand densities may be underestimated because most data used in model development came from natural stands.

The number of precommercial thinnings required is directly related to the size of trees cut at each thinning. GSL and site quality influence the number of precommercial thinnings required if periodic thinnings are made to a constant GSL. For spruce-fir on site index 50 land, a GSL of 60 or above requires more than one precommercial thinning. At site index 70, the GSL may be increased to 100, and at site index 90, the GSL may be increased to 140, with only one precommercial thinning

required. For lodgepole pine, at site indexes 50 and 60, thinnings to GSLs above 60 require more than one precommercial thinning. For site index 70, GSLs of 80 and below result in only one precommercial thinning. The manager does have some flexibility by increasing GSLs with successive thinnings to overcome limitations on a number of precommercial thinnings with higher initial GSLs.

Height Growth

Periodic dominant and codominant height growth of both spruce-fir and lodgepole pine increases with site index and decreases with age, but is influenced little by GSLs in the range examined. However, since fewer and, therefore, taller trees remain after each thinning from below, the mean height of residual trees is negatively correlated with GSL.

Basal Area Increment

Periodic basal area increment is positively correlated with stand density and site quality. Since residual basal area increases in a stand until average diameter reaches 10 inches, at which point thinning reduces basal area to a fixed GSL amount, the rate of basal area growth for a given GSL is not constant over time. Periodic basal area increment is greater at higher GSLs, but the rate of increase declines at higher densities. Basal area increment is also greater at higher site indexes, and differences between site classes become greater with higher GSLs.

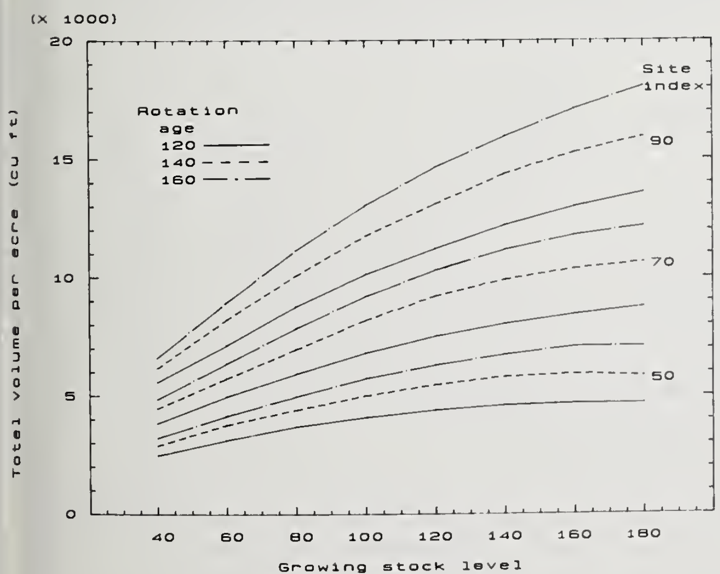

Figure 1.--Estimated total cubic-foot volume production per acre in spruce-fir stands in relation to growing stock level, site index, and rotation age.

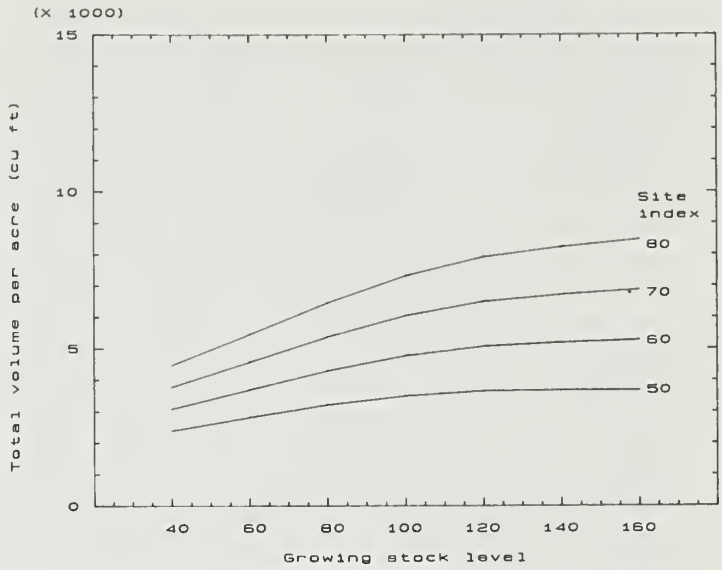

Figure 2.--Estimated total cubic-foot volume production per acre in lodgepole pine stands in relation to growing stock level and site index for an 80-year rotation age.

Total Cubic-Foot Volume Production and Increment

Cubic-foot volume production is related to stand density, site quality, and rotation age for both spruce-fir and lodgepole pine (figs. 1, 2, 3). Volume production includes periodic removals and final harvest. Although cubic volume production increases with increasing GSL and site index, the rate of increase decreases as GSL increases. Cubic volume production increases modestly at GSLs above 180 for spruce-fir and

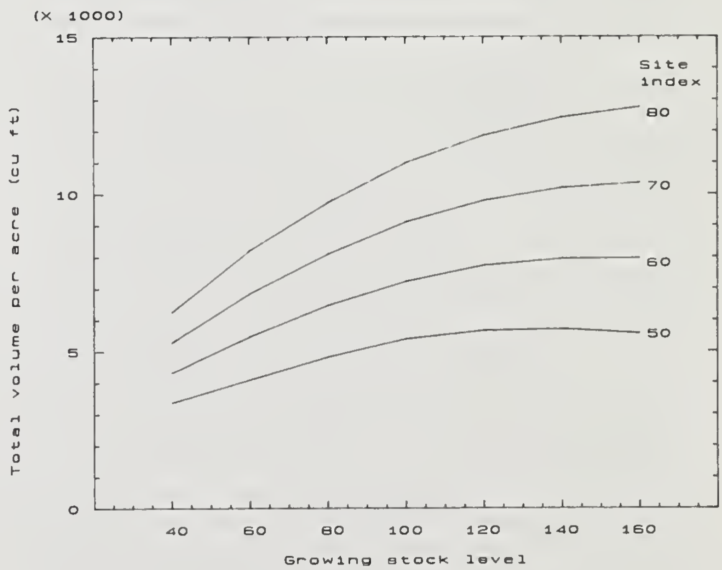

Figure 3.--Estimated total cubic-foot volume production per acre in lodgepole pine stands in relation to growing stock level and site index for a 120-year rotation age.

above 160 for lodgepole pine on all but site index 50 lands. Volume production for spruce-fir is progressively greater at increased site index. For lodgepole pine, however, the increase in production is relatively constant with increasing site index. While direct comparison of lands with equal site index is not possible for the two forest types, productivity of site index 50 and 70 lodgepole pine stands with a 120-year rotation is greater than site index 50 and 70 spruce-fir stands. At higher site indexes, spruce-fir is more productive than lodgepole pine.

Mean annual total cubic volume increment at rotation age is also related to stand density and site quality, but rotation age has little influence on mean annual increment (figs. 4, 5). The relative lack of effect of rotation age is not surprising, because repeated thinnings extend the point of culmination of mean annual increment to a plateau often extending over a wide range of stand ages. Mean annual increment is again progressively greater with increasing site index for spruce-fir, but for lodgepole pine the site index effect remains relatively constant.

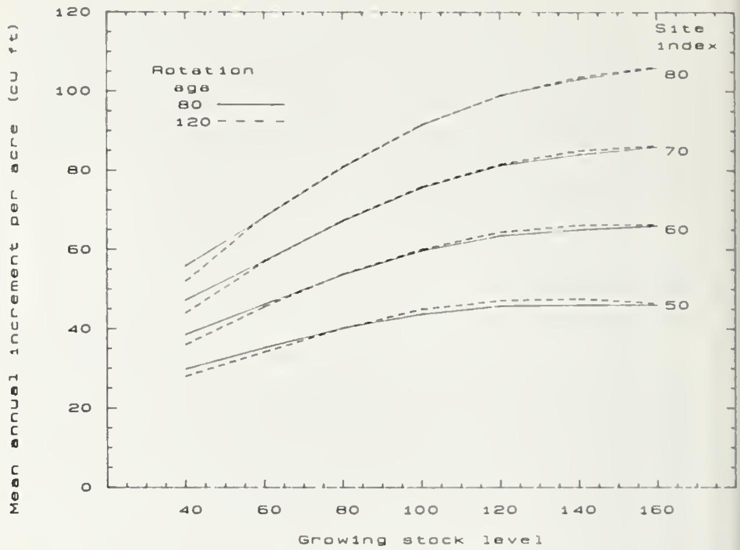

Figure 5.--Estimated mean annual total cubic-foot volume increment at rotation in lodgepole pine stands in relation to growing stock level, site index, and rotation age.

Board-Foot Volume Production and Increment

Board-foot volume production is related to stand density, site quality, and rotation age for spruce-fir (fig. 6) and lodgepole pine. Although board-foot volume production increases with increasing GSL and site index, the rate of increase diminishes with greater GSLs. Timber production increases only slightly at GSLs above 180 for spruce-fir and above 160 for lodgepole pine on all but site index 50 lands. Spruce-fir sawtimber production is again progressively greater at increased site index. However, lodgepole pine production is directly correlated with increasing site index.

Mean annual board-foot volume increment at rotation age is also related to stand density and site quality, and rotation age has a greater influence on board foot than on total cubic mean annual increment (figs. 7, 8). Average tree size increases with longer rotations, and tree size has a pronounced effect on merchantable volume calculations. Mean annual increment is again progressively greater with increasing site index for spruce-fir, but for lodgepole pine the site index effect remains relatively constant.

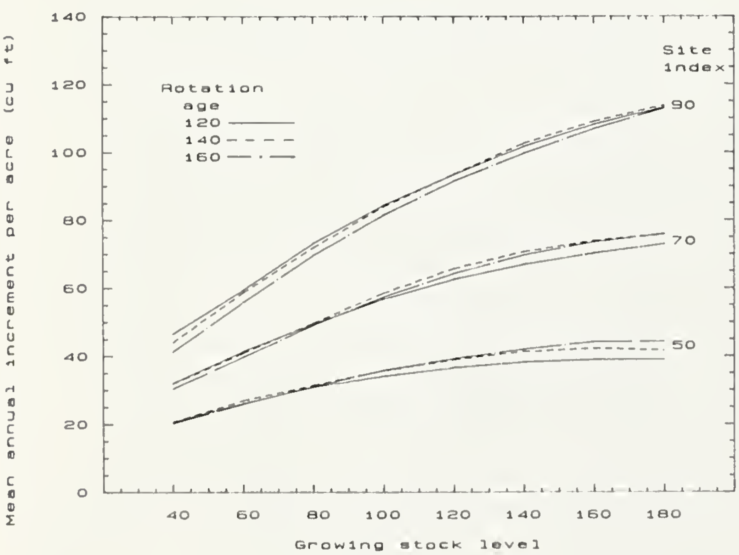

Figure 4.--Estimated mean annual total cubic-foot volume increment at rotation in spruce-fir stands in relation to growing stock level, site index, and rotation age.

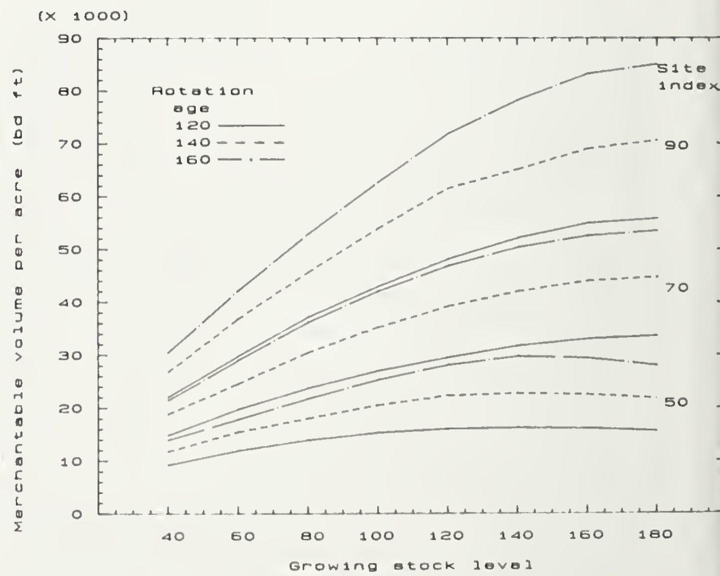

Figure 6.--Estimated board-foot volume production per acre in spruce-fir stands in relation to growing stock level, site index, and rotation age.

Management Caution

Growth responses and productivity estimates presented appear reasonable within the limits of current knowledge. However, no spruce-fir or lodgepole pine stand has been under management for the better portion of a rotation, and in some situations, the simulations extend beyond the limits of the available data base. Comparisons of estimated values with actual values from permanent plots are needed to verify the growth and yield projections. An example of such a comparison is the levels-of-growing-stock study in lodgepole pine that will be visited on the field trip.

Reference Curves for Stocking Charts

A major provision of the National Forest Management Act of 1976 is that forest lands in the National Forest System be maintained at appropriate stocking to secure maximum benefits of multiple-use, sustained yield management. Several formats are available for stocking guides for the major forest types. An example is the growing stock levels developed by Myers (1967) for ponderosa pine and used in the above yield projections to index stand density after partial cutting.

The Forest Service selected the Gingrich (1967) stocking guide format as a standard to assist with the consistent application of stocking guidelines (Ernst and Knapp 1985). The relative simplicity of the Gingrich stocking guide makes it especially attractive as a communication tool when land managers must consider multiresource management. In addition, Curtis (1970) demonstrated the ease of converting from many other frequently used stand density measures. However, stocking charts apply only to a specific forest type, often a single species, and simple stand structures with unimodal

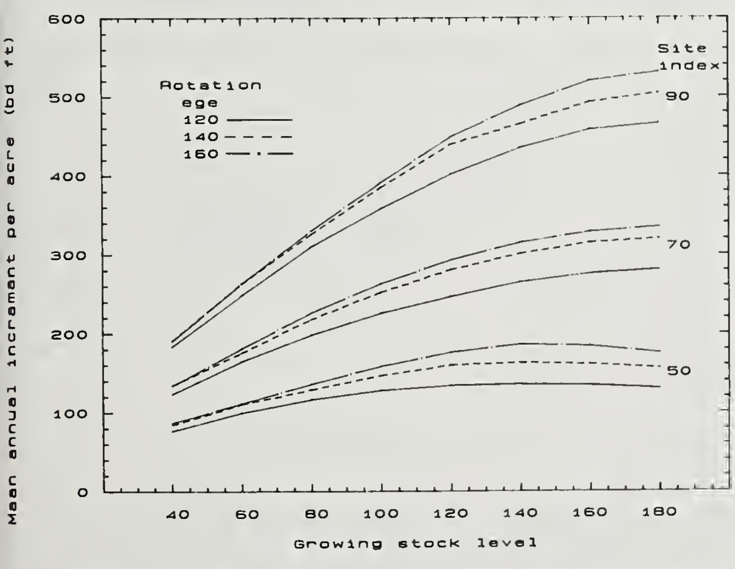

Figure 7.--Estimated mean annual board-foot volume increment at rotation in spruce-fir stands in relation to growing stock level, site index, and rotation age.

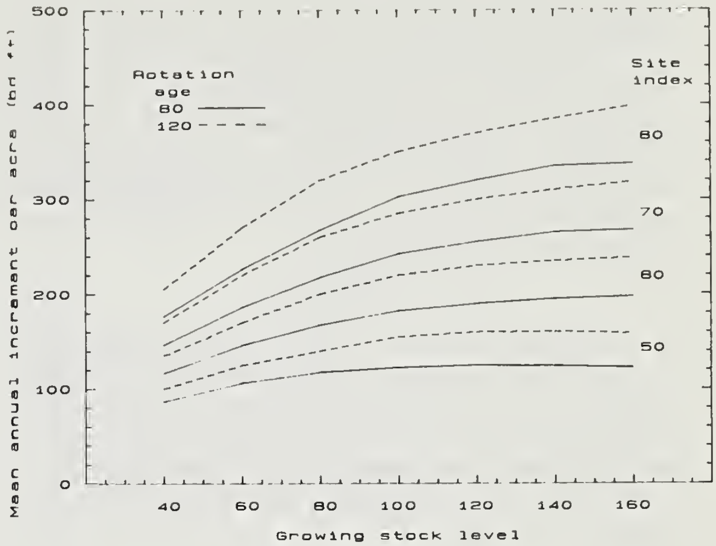

Figure 8.--Estimated mean annual board-foot volume increment at rotation in lodgepole pine stands in relation to growing stock level, site index, and rotation age.

diameter distributions. In the central Rocky Mountains, these limitations are generally not critical due to relatively simple species composition and structure in the majority of forest stands.

The Gingrich guide displays stand basal area as a function of number of trees and quadratic mean diameter (DQ). The reference level for the guide is the absolute stand density at average maximum competition. Many stocking charts have been developed from tree-area relationships, and this procedure is well documented (Chisman and Schumacher 1940, Gingrich 1967). The procedure for developing the reference level for forest types where tree-area relationships are not available has not been adequately documented.

Earlier this year, the Rocky Mountain Region provided a data set for natural stands to develop reference levels for stocking charts of the Engelmann spruce-subalpine fir, lodgepole pine, and aspen forest types. Stand selection criteria for the analysis included: (1) the tree species used for site index determination must correspond to the recorded forest type; (2) at least 80% of the species composition, in terms of basal area, must match the forest type; (3) at least 90% of the sample points in the stand must have tallied trees and the DQ must be at least 1.0 inch; and (4) stands must be relatively even-aged. It was not possible to directly screen this fourth criterion from the elements in the data base. As an alternative, a criterion of narrow diameter distribution was used, with stands having at least 80% of their basal area in diameter classes 1 to 9 inches, 5 to 16 inches, or 9 inches and larger being selected. The resulting data set contained 4,440 spruce-fir, 7,918 lodgepole pine, and 2,204 aspen stands.

The goal of the analysis was to derive the reference level known as the average maximum density (AMD) relationship--stand basal area per acre (BA) as a function of trees per acre

(TPA)--directly from the data set. The AMD curve is an average upper limit of observed BA across the range of TPA. Various selection criteria were applied to further select the average maximum BA values for each forest type, while providing an adequate representation of the range of TPA. After many trials and examination of resulting AMD curves, stands with the upper 2% of stand density index (SDI) values were selected (Reineke 1933). SDI for each stand was computed using the following equation:

$$SDI = TPA\ (DQ/10)^{1.6} \qquad [1]$$

Characteristics of stands with SDI values in the upper 2% for each forest type are summarized in table 1. The analysis to develop the AMD curve for each forest type involved two major steps. First, the data points were plotted on a lnDQ versus lnTPA graph, where ln is the natural logarithm. A simple linear regression was fit to the transformed data of the form:

$$\ln DQ = b_0 + b_1 \ln TPA \qquad [2]$$

The next step was to transform the estimated coefficients from the first step to a BA versus TPA scale. These transformed estimates were then used as starting values in nonlinear regression of the form:

$$BA = b_2\, TPA^{b_3} \qquad [3]$$

Table 1.--Characteristics of natural stands with SDI values in the upper 2% for each forest type.

Characteristic	Mean	Min.	Max.
Spruce-fir			
Trees per acre	863	239	2,700
Basal area per acre (ft2)	323	240	425
Average diameter (inches)	8.9	4.0	17.8
SDI	626	575	757
Age	128	62	256
Site index (feet)	70	40	102
Lodgepole pine			
Trees per acre	2,185	662	6,700
Basal area per acre (ft2)	249	180	316
Average diameter (inches)	5.0	2.3	9.1
SDI	609	556	728
Age	94	40	181
Site index (feet)	52	26	81
Aspen			
Trees per acre	1,172	646	2,920
Basal area per acre (ft2)	307	264	359
Average diameter (inches)	7.2	4.1	9.9
SDI	644	592	755
Age	83	46	141
Site index (feet)	66	39	89

Table 2.--Results of fitting the curve of basal area over number of trees per acre (eq. 2) for subalpine stands representing the upper 2% SDI values.

Forest type	b_2	b_3	R^2	S_{y+x}
Engelmann spruce-subalpine fir	1287.091	-0.207	0.459	30.4
Lodgepole pine	1034.509	-0.189	0.586	18.8
Aspen	918.340	-0.156	0.275	24.1

Results of the nonlinear regression analysis are summarized in table 2. Data and resulting curves are shown in figures 9, 10, and 11 for spruce-fir, lodgepole pine, and aspen, respectively. The R^2 values in table 2 are the proportion of the corrected total sums of squares of basal area accounted for by the regression.

The AMD curves for the three forest types are shown together in figure 12. As expected, the lodgepole pine curve lies below the curve for more shade tolerant spruce and fir. The spruce-fir curve also lies above the aspen curve for stand densities less than approximately 750 trees per acre, but the aspen curve is the highest for dense stands. This may result from dense regeneration characteristics of aspen, which generates suckers from an existing mature root stock.

The next step in developing the stocking charts will be to superimpose management zones in the area below the AMD curves for each species. These management zones should be based on estimated timber production from simulations as described above. This step will be done with interaction from forest managers to ensure management goals can be met within the zone.

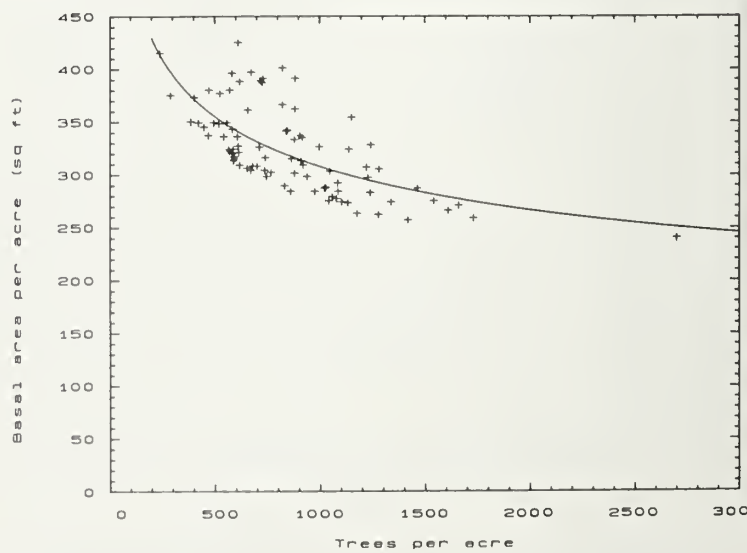

Figure 9.--Relationship of basal area to trees per acre for spruce-fir plots with upper 2% stand density index values.

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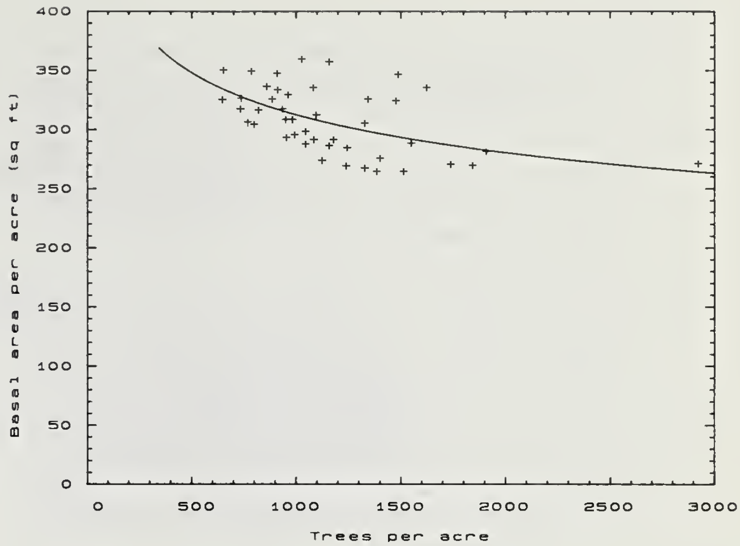

Figure 11.--Relationship of basal area to trees per acre for aspen pine plots with upper 2% stand density index values.

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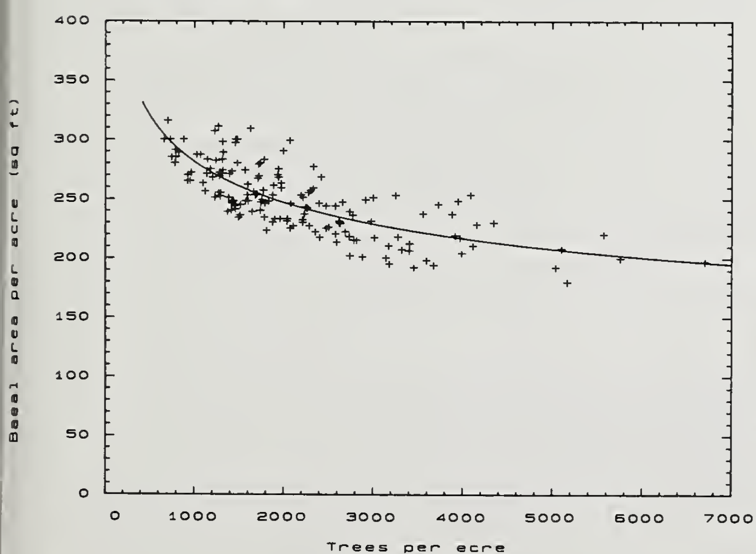

Figure 10.--Relationship of basal area to trees per acre for lodgepole pine plots with upper 2% stand density index values.

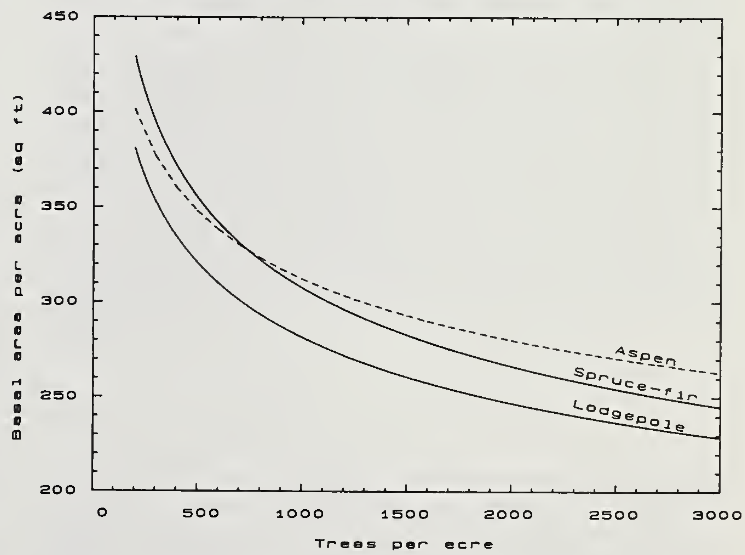

Figure 12.--Comparison of average maximum density curves for spruce-fir, lodgepole pine, and aspen stands.

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245 Growth and Yield of Aspen in the Central Rocky Mountains

H. Todd Mowrer[1]

Abstract--This paper provides an overview of the mensurational procedures available for aspen management in the central Rocky Mountains, and compares the relative precision of two aspen growth and yield models using a Monte Carlo technique.

An increased interest in aspen in the mid-1970s resulted in a mensurational research effort to provide improved management tools for the central Rocky Mountains. The resulting studies have improved prediction techniques for aspen growth and yield, integrated many of these techniques into two growth and yield models, and provided estimates of the reliability of the resulting projections. The variance estimation technique described here is applicable not only to growth and yield models, but to many other types and combinations of natural resource models as well.

Aspen Management Tools

Site quality indicates the interaction of genetic and environmental factors on tree growth. Site index, a commonly used indicator of site quality, expresses the relationship between tree height and age. New site index curves for aspen (Edminster et al. 1985) provide an improved basis for evaluating the productive potential of the species, particularly at earlier ages.

The culmination of volume growth, or the point of maximum mean annual growth, indicates the maximum productive potential of an aspen stand. Site index serves as a useful predictor for this maximum. With additional information on stand basal area, productivity of aspen stands at culmination of growth may be estimated by a recently published set of equations predicting mean annual increment at volume culmination (Mowrer 1986a).

Periodic tree growth may be calculated from temporary plot measurements in aspen using radial growth increment and bark thickness relationships (Mowrer and Edminster 1985). This radial increment, as well as tree age, may be efficiently measured in the field using recently published measurement techniques for aspen (Mowrer and Shepperd 1987).

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Volume yield for individual trees may be estimated using tables, equations, and point sampling factors developed by Edminster et al. (1982). When point samples are measured within an even-aged clone of aspen, average stand volume may be estimated directly from basal area and average height (Shepperd and Mowrer 1984).

These tools help in evaluating the productive potential of an aspen stand and in measuring the current level of stand performance. Estimates of future stand development can be obtained from two growth and yield models for pure, even-aged stands of aspen in the central Rocky Mountains.

Growth and Yield Models

Growth and yield models are classified by the spatial resolution with which they predict forest growth. The lowest level of spatial resolution is provided by whole stand models, which predict changes in conditions from stand average values. Models of this type lack the ability to predict diameter-class product information, but have the advantage of providing more precise estimates of stand volume, as described later. The model with highest resolution first predicts the growth of individual trees, and then aggregates these values into diameter classes to provide product information. Between these two extremes, a diameter distribution model assumes an underlying probability distribution to determine the numbers of stems in diameter classes.

Whole Stand Model

RMYLD2 is a computer program to predict stand-level estimates of growth and yield of even-aged and two-storied stands of five tree species in the central Rocky Mountain region. RMYLD2 is available in versions for IBM-compatible microcomputers, for U.S. Forest Service Data General mini-

computers, and for mainframe computers. An aspen subroutine for RMYLD2 provides growth and yield estimates for thinned and unthinned stands across a wide range of conditions (Edminster and Mowrer 1984). Model simulations using this subroutine have been used to explore the effect of thinning on aspen volume yield for various combinations of site quality, rotation age, and thinning intensity (Edminster and Mowrer 1984, Mowrer 1987b).

To compare models, a set of yield estimates were simulated across a range of initial stand conditions for site indices ranging from 40 to 90 feet at 80 years. Five 10-year growth projections were made, based on identical initial conditions. Figure 1a shows the gross total volume per acre estimated by the aspen subroutine to RMYLD2, with initial conditions running from left to right across the range of site indices at the front of the figure, and for five successive 10-year projections toward the rear of the figure. Projections follow an expected trend, with higher sites producing greater yields.

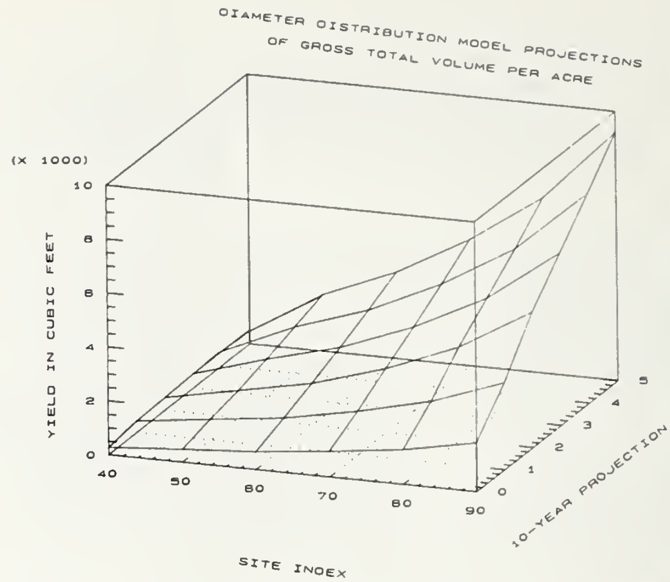

Figure 1b.--Gross total cubic foot volume per acre predicted by the diameter distribution model (ASPNORM) for the same initial site conditions.

Diameter Distribution Model

A subset of the data used to calibrate the aspen subroutine for RMYLD2 was used to develop a second growth and yield model for aspen. ASPNORM (Mowrer 1986b) predicts the growth and yield of pure, even-aged aspen stands that maintain a normal (or bell-shaped) probability distribution of stems per acre across diameter classes. Accumulation of basal area, height, and volume across these 1-inch diameter classes provides product information for aspen clones meeting the normal diameter distribution requirement.

Figure 1b shows the set of yield estimates for the diameter distribution model corresponding to those in figure 1a made by the stand average model, based on the same set of initial stand conditions. Figure 1c shows the production surfaces for both models on the same set of axes for comparison. The differences in initial volumes estimated by the two models are due to the differences in the estimation process. With increasing projection lengths, the diameter distribution model estimates less volume on lower sites than the stand average model, while for sites above 60 feet, it estimates successively more volume. When two models, based on the same calibration data as these are, provide differing results, an opportunity exists to compare the reliability of both sets of estimates.

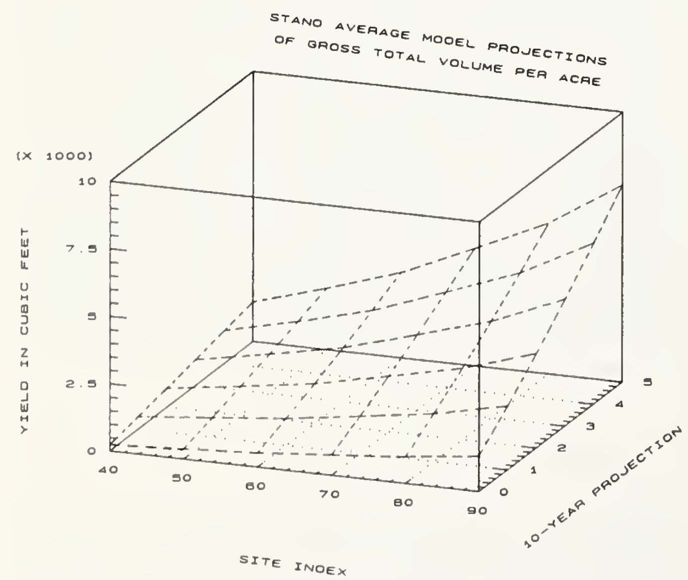

Figure 1a.--Gross total cubic foot volume per acre predicted by the whole stand model (RMYLD2) for a range of initial site conditions.

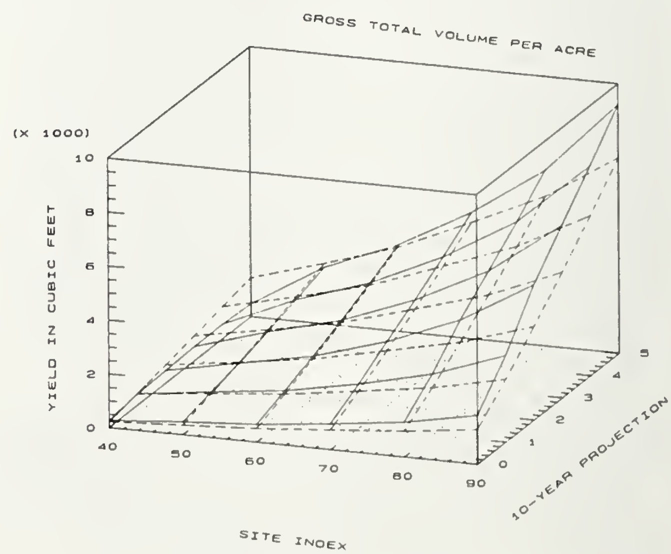

Figure 1c.--Response surfaces from 1a and 1b superimposed on the same set of axes. The diameter distribution model underestimates volume for low sites and overestimates volume on high sites with respect to the whole stand model.

Model Validation

The usual measure of reliability incorporates both bias and variance terms. Bias refers to a systematic trend in under- or overestimation of the true (but often unknown) value, while variance relates to the variability of the estimates about the true value. Model developers have addressed the bias term by comparing model predictions against repeated observations from permanent growth plots. Estimates of model bias are available for ASPNORM (Mowrer 1986b) and RMYLD2.[2]

Variance in model predictions has seldom been calculated, however. Variance in the form of sampling error is always present in forest inventory data used to initiate model projections. As repeated growth projections are made, stand variables predicted in the prior period become predictors upon which estimated values for the next period are based. Errors in predictor or independent variables accumulate in the predicted or dependent variable at each projection. Thus, errors in model variables are propagated within the model over repeated projections.

A Monte Carlo technique for estimating the variance introduced by repeated projections in growth and yield models has been developed and applied to the diameter distribution model, ASPNORM, by Mowrer and Frayer (1986) and the stand average model, RMYLD2, by Mowrer (1987a). This methodology can be adapted to provide variance estimates for growth and yield projections made by most computer models.

Monte Carlo Technique

Monte Carlo techniques involve repeated generation of random values from a known distribution. These values reflect random variations in the relationships between the variables necessary to initialize the models. Periodic model predictions represent an unknown transformation on these input variables as growth projections are made. Since this transformation is usually very complex, exact variance estimators can seldom be developed. The variance of the output variables can be estimated over a number of repetitions of the Monte Carlo process, as described in detail by Mowrer and Frayer (1986).

To provide a comparison of relative precision, an identical Monte Carlo technique was applied to both models. Appropriate input values for the diameter distribution model and the whole stand model were simulated using the Monte Carlo procedures based on the same set of plot sample data. These values are displayed graphically as initial conditions at projection zero across the front of figure 2. The cumulative means from 26 successive simulated samples from this plot provide a range of variability in input values, displayed from left to right across the front of the figure. Responses from both models are measured on the vertical axis as the coefficient of

[2]Edminster, Carleton B. 1987. Growth and yield relationships for even-aged stands of aspen in the central Rocky Mountains. Manuscript in preparation.

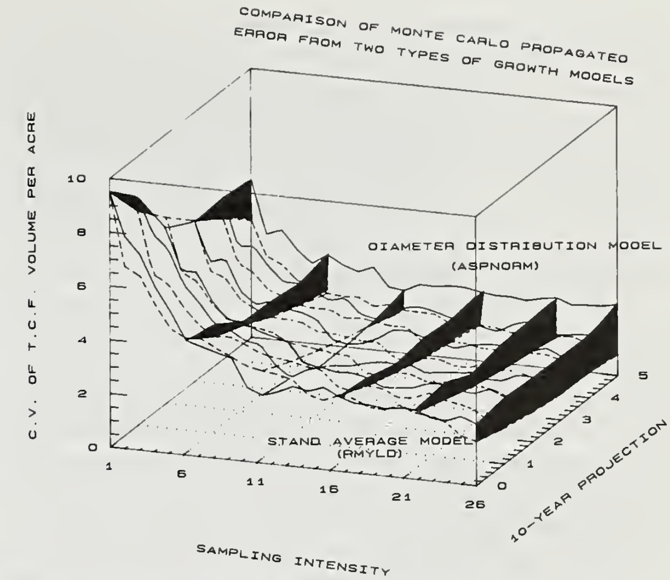

Figure 2.--Two response surfaces for Monte Carlo estimates of propagated error over five 10-year projections and increasing cumulative sampling intensity. Shaded areas represent areas where the variability in estimated gross total cubic foot volume by the diameter distribution model exceeds that of the whole stand model.

variation (the standard error divided by the mean expressed as a percent) of gross total volume calculated at each sampling intensity for initial conditions and for five resulting 10-year projections. The coefficient of variation (c.v.) provides a unitless measure of relative variability in the volume estimated by the model.

To aid in visualizing trends in relative model precision in figure 2, segments of planes passing through six levels of constant sampling intensity have been shaded where the relative variation in the gross total cubic foot volume estimated by the diameter distribution model exceeds that of the whole stand model. In general, these shaded areas increase in height with increasing projection length, reflecting greater differences in relative model precision. These results indicate that the less complex whole stand model (RMYLD2) makes more precise stand volume estimates than the more complex diameter distribution model (ASPNORM).

The advantage to this Monte Carlo method is that it can be applied externally to a model with little knowledge of the internal mechanisms of model prediction. The disadvantages are that the results are specific to the plot data used for the simulation, and that it does not include sources of error variation due to calibration errors in the regression coefficients, thereby underestimating total error.

Conclusions

The Monte Carlo results provide a basis for inferring that increases in model resolution (predicting changes in smaller units) is at the expense of model precision (the degree of certainty we may place in those predictions). We may estimate

the distribution of diameters within a stand, but will know the resulting stand values less precisely than if they were predicted directly as stand average values. Unnecessarily increasing numbers of model estimates or the level of model resolution will contribute to increased levels of uncertainty in the resulting predictions. The implication is that resource managers should select the model that provides the information required by the decision at hand and predicts it at a level of resolution that does not unnecessarily exceed information requirements.

Just because results are printed on computer paper, the user should not assume model predictions are exact, whether they are estimates of volume per acre or approximations of associated variance. Models incorporating negative feedback to control prediction variability will appear to have less than actual error levels under the Monte Carlo simulation method. Proper interpretation of the results of this technique requires an understanding of the actual sources of estimated errors.

The Monte Carlo technique is useful not only for growth and yield models, but for virtually any model or sequence of models. This allows an assessment of the relative reliability of model projection sequences as they are incorporated into the planning process.

With the widespread proliferation of computers, it is not uncommon for several computer models to be available to predict the same phenomenon. While convenience should be considered when determining which model to use, the quality of model predictions should be an overriding concern to those making natural resource decisions. Increased model sophistication requires increased user sophistication in selecting the appropriate model for each set of circumstances.

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Application of Growth and Yield Models for Forest and Project Planning

Daniel M. Greene[1]

Abstract--This report summarizes how growth and yield models have been used for Forest and Project Planning in the Rocky Mountain Region and lists future needs of Growth and Yield Systems.

Growth and yield simulation models have been an integral part of the Rocky Mountain Region Planning Process since development of the 1975 Timber Management Plans. At that time or shortly after, the following computer programs to compute yield tables were available from the Rocky Mountain Forest and Range Experiment Station:

1. PONYLD (Myers 1971)
2. LPMIST (Myers et al. 1971)
3. SPRYLD (Alexander et al. 1975)
4. SWYLD2 (Myers et al. 1976)

These programs were designed to simulate even-aged, managed stands. They were not designed to simulate existing unmanaged stands that were already 80 to 120 years old.

In order to simulate older existing stands for development of the Timber Management Plans, the Region developed an "in-house" model; R2GROW (Greene and Gryczan 1975). R2GROW is a 2-inch diameter class model for simulating average growth of forest-wide condition classes. R2GROW was used for simulating existing stands primarily due to the capability to match inventory volumes at the start of a simulation.

In 1977, the station combined the four separate computer programs; PONYLD, LPMIST, SWYLD2 and SPRYLD into a single modular program entitled RMYLD (Edminster 1978). RMYLD was designed to simulate managed even-aged stands of mostly pure species composition and is a whole stand model.

Starting in 1979, RMYLD and R2GROW were the sole growth and yield models used for the development of the current Rocky Mountain Region Forest Plans. RMYLD was used primarily for the simulation of existing seedling or sapling stands and regenerated stands. R2GROW was used to simulate existing poletimber or sawtimber stands.

Currently the Grand Mesa, Uncompahgre, and Gunnison National Forest is undergoing a major re-analysis of their Forest Plan due to a remand by the Secretary's Office. RMYLD2, a major revision to RMYLD, is being used. The use of RMYLD2 is significant in that the user may input a percent of the stand that is stockable and average defect. RMYLD2 also includes a module for simulating the Aspen forest type.

Forest Planning

Growth and yield simulation programs have been used in the Rocky Mountain Region primarily for the development of the Forest Plans. In order to understand how these models fit into the Forest Planning Process, it is necessary to understand some of the components of the process. Major components that will be discussed are:

- Forest Inventory Information
- Identifying Forest Land Tentatively Suitable for Timber Production
- Development of Timber Analysis Areas (Stratification)
- Development of Prescriptions for each Analysis Area
- Development of Yield Tables for each Prescription using RMYLD2 and R2GROW
- Analysis of Alternatives and Scheduling using FORPLAN
- FORPLAN Outputs that are Dependent on the Timber Yield Tables

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Refer to figure 1 for an overview of the Forest Planning process displaying where growth and yield models fit in. The Grand Mesa, Uncompahgre, and Gunnison National Forest Plan is currently being re-analyzed and will be used as an example of how growth and yield models are used in the forest planning framework.

Inventory

A recent inventory has been completed for the Grand Mesa, Uncompahgre, and Gunnison National Forests. Site specific inventory information from various sources is stored in R2RIS; Region 2 Resource Information System (R2 FSH 6609.21). Tree data samples (sample plot or stand data from the timber inventory) are stored on the Stand Support Tape System (R2 FSH 2409.26d). The information was combined from both sources into the RPA Data Base in order to generate Forest Inventory Tables. The system is flexible so that the information may be re-stratified as necessary to address the issues and concerns of managing the Forest. Refer to figure 2 for an overview of the inventory process.

Six products of the inventory were:

1. Full implementation of the Resource Information System (R2RIS) completed by Forest and District staff.

2. Up-to-date district stand maps completed by Forest and District Staff.

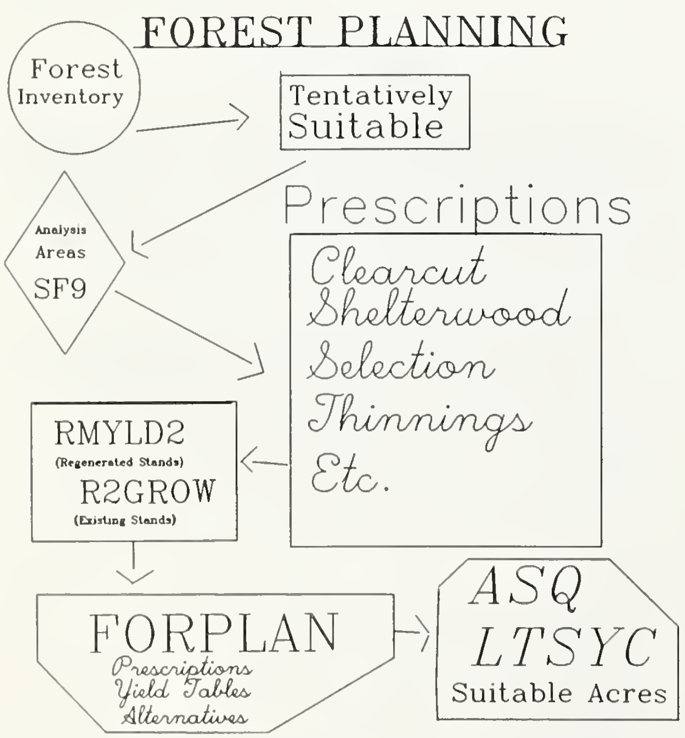


Figure 1.--Overview of forest planning process as it relates to growth and yield models.

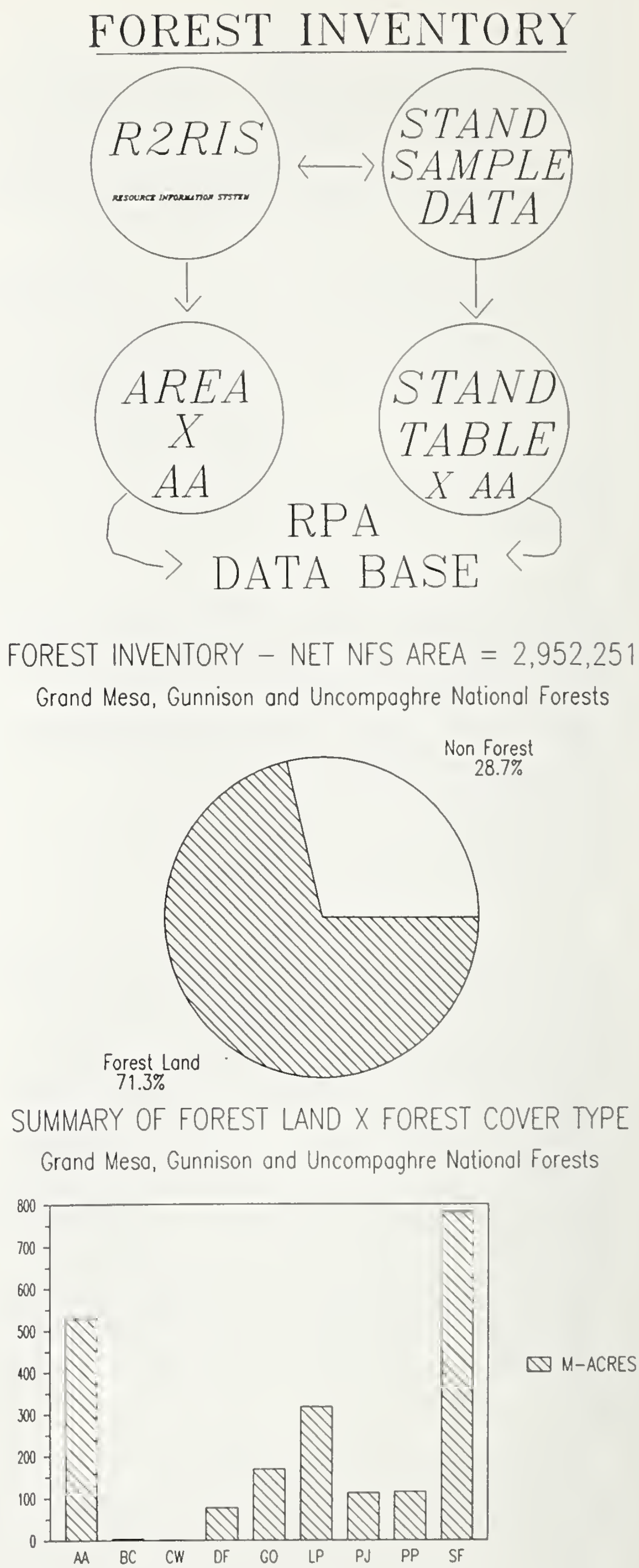


Figure 2.--Overview of the Rocky Mountain Region forest inventory process.

"All RIS sites on the Forest are currently mapped on USGS quads. The RIS maps will be the framework for all maps completed for the reanalysis." (Grand Mesa, Gunnison, and Uncompahgre NFs, Draft Addendum to Planning Action 2).

3. Per acre stand tables for each forest cover type and stand size class completed by the Regional Office.
4. A set of tables displaying total acres, total board and cubic feet volumes, etc. for each forest type and tand size class completed by the Regional Office.
5. A permanent set of field samples stored on a forest stand support tape for post stratification into forest condition classes.
6. An updated RPA data base merging per acre data from field samples with total areas from R2RIS.

The use of the R2RIS and field sample data is summarized as follows (Grand Mesa, Uncompahgre, and Gunnison, Draft Addendum to Planning Action 2, May 1987):

"New timber inventory data will be used. This new timber data provides the site specific on-the-ground analysis required by Deputy Assistant Secretary Douglas W. MacCleery's decision on July 31, 1985. It also provides the link between the linear program allocations and multiple use benefits, which are considered later in this study.

Since the Plan was issued, the "Resource Information System" (RIS) has become the standard data base for the Rocky Mountain Region. Forest Service Handbook-FSH 6609.21- displays information and coding structure for the Forest's data base. RIS provides specific resource information for each land unit or site on the Forest.

RIS will be used in the analysis area (AA) identification process, for determining land not appropriate for timber production, for effects analysis, and for monitoring.

After the basic inventory tables were completed, the forest generated area totals for each timber analysis area (AA-forest cover type and condition class) from the R2RIS data base. For each of these analysis areas, a single average per acre stand table was generated from the Stand Support Tape System (Timber Inventory) using the VARGEN computer program. These average per acre tables were used as input to the Growth and Yield Models for developing yield tables for each applicable prescription.

Tentatively Suitable Lands

Part of the Analysis Area identification process is to determine lands that are tentatively suitable for the production of industrial wood products. These acres will be analyzed with the FORPLAN computer model. Yield tables need to be developed for all of the tentatively suitable acres.

"Tentatively suitable lands, identified in accordance with the process set forth in FSH 2409.13-21, are a fixed input to the forest planning model in the establishment and evaluation of benchmarks and alternatives" (FSH 2409.13).

The following tabulation displays the tentatively suitable acres for the Grand Mesa, Uncompahgre, and Gunnison National Forests Plan Re-analysis.

Grand Mesa, Uncompahgre and Gunnison National Forests land capable, available and tentatively suitable for timber production.

Criterion	Area-Acres
Non-Forest	
-Non-forest land	837,294
-Water	10,515
Subtotal	847,809
Capable Forest Land Withdrawn From Timber Production	
-National Wilderness Preservation System	269,116
-Research Natural Areas	
(1) Gothic	
(2) Escalante	237
-Wilderness Study Area	
(1) Fossil Ridge	33,535
-Further Planning Area	
(1) Recommended Portion of Cannibal Plateau	6,801
-Administrative Sites	2,477
-Campgrounds	7,472
-Cultured Areas	400
Subtotal	320,038
Forest Land Incapable of Producing Industrial Wood	417,613
Not Physically Suited	
-Restocking within 5 years cannot be assured	8,917
-Irreversible Resource Damage	41,223
-Inadequate Response Information	1,751
Subtotal	51,891
Unsuitable Total	1,637,351
Total Net Forest Acres	2,952,251
Tentatively Suitable Land for Timber Production	1,314,900

At this point the acres of the Forest that must have associated yield tables developed using growth and yield models has been narrowed down. Refer to figure 3 for a graphic display of Tentatively Suitable Lands identified by the re-analysis of the Grand Mesa, Uncompahgre, and Gunnison National Forests.

Analysis Areas

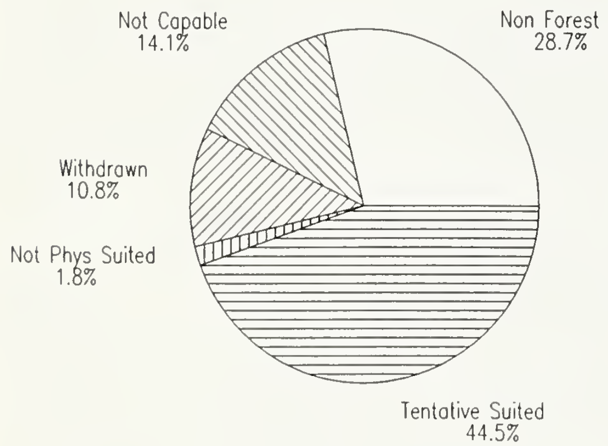
Lands tentatively suitable for timber production were subdivided into timber analysis areas. These analysis areas are expected to respond similarly to management practices in order to develop yield tables that are responsive to issues and concerns. Timber Analysis Areas defined for the Grand Mesa, Uncompahgre, and Gunnison National Forest Plan Re-analysis are:

Aspen Forest Cover Type
1. Conifer Invaded Aspen-Seedling/Sapling (MIX7)
2. Conifer Invaded Aspen-Poletimber (MIX8)
3. Conifer Invaded Aspen-Sawtimber (MIX9)
4. Predominately Aspen-Seedling/Sapling (AA7)
5. Predominately Aspen-Poletimber (MIX8)
6. Predominately Aspen-Sawtimber (MIX9)
7. Self Regenerating Aspen (SELF-R)

Lodgepole Pine Forest Cover Type
1. Nonstocked (LP6)
2. Seedling/Sapling (LP7)
3. Poletimber (LP8)
4. Sawtimber (LP9)
5. Mistletoe Infected (LPMIS)
6. Stagnated (LPSTAG)

TENTATIVELY SUITABLE FOR TIMBER PRODUCTION

Grand Mesa, Gunnison and Uncompaghre National Forests



TENTATIVELY SUITABLE X FOREST COVER TYPE

Grand Mesa, Gunnison and Uncompaghre National Forests

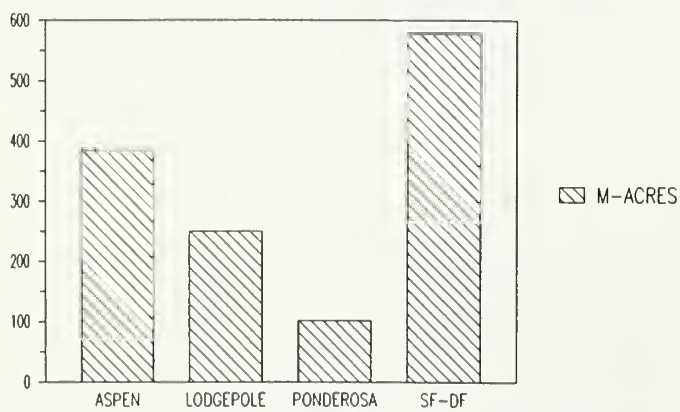


Figure 3.--Forest land tentatively suitable for timber production.

Ponderosa Pine Forest Cover Type
1. Nonstocked (PP6)
2. Seedling/Sapling (PP7)
3. Poletimber (PP8)
4. Sawtimber (PP9)

Spruce Fir and Douglas-fir Cover Types
1. Nonstocked (SF-DF-6)
2. Seedling/Sapling (SF-DF-7)
3. Poletimber (SF-DF-8)
4. Sawtimber (SF-DF-9)

Refer to figure 4 for a graphic display of timber analysis areas developed for the Grand Mesa, Uncompahgre and Gunnison Re-Analysis.

Prescriptions

Management prescriptions which could be applied to address the issues and concerns are developed for each timber analysis area.

> "Develop management prescriptions, including timber production functions, on a per acre basis for all forest land that is identified as tentatively suitable. In accordance with 36 CFR 219.27, integrate all prescriptions for tentatively suitable lands to meet one or more resource emphases and intensities for a unit of land. Complete prescription development before evaluating benchmarks and forest plan alternatives to ensure consideration of an adequate range of prescriptions in meeting forest plan objectives" (FSH 2409.13).

Each prescription is simulated using a RMYLD2 or R2GROW. Following is a sample Management Area Prescription for uneven-aged management: (Grand Mesa, Uncompahgre, and Gunnison NFs, Draft Addendum to Planning Action 2)

Management Area Prescription 7F

Provide for uneven-aged sawtimber production on slopes less than 40%.

Management emphasis is on wood-fiber production and utilization of large roundwood of a size and quality suitable for sawtimber. The harvest method by forest cover type is group selection in Engelmann spruce-subalpine fir. Release and weed occurs to harvested areas.

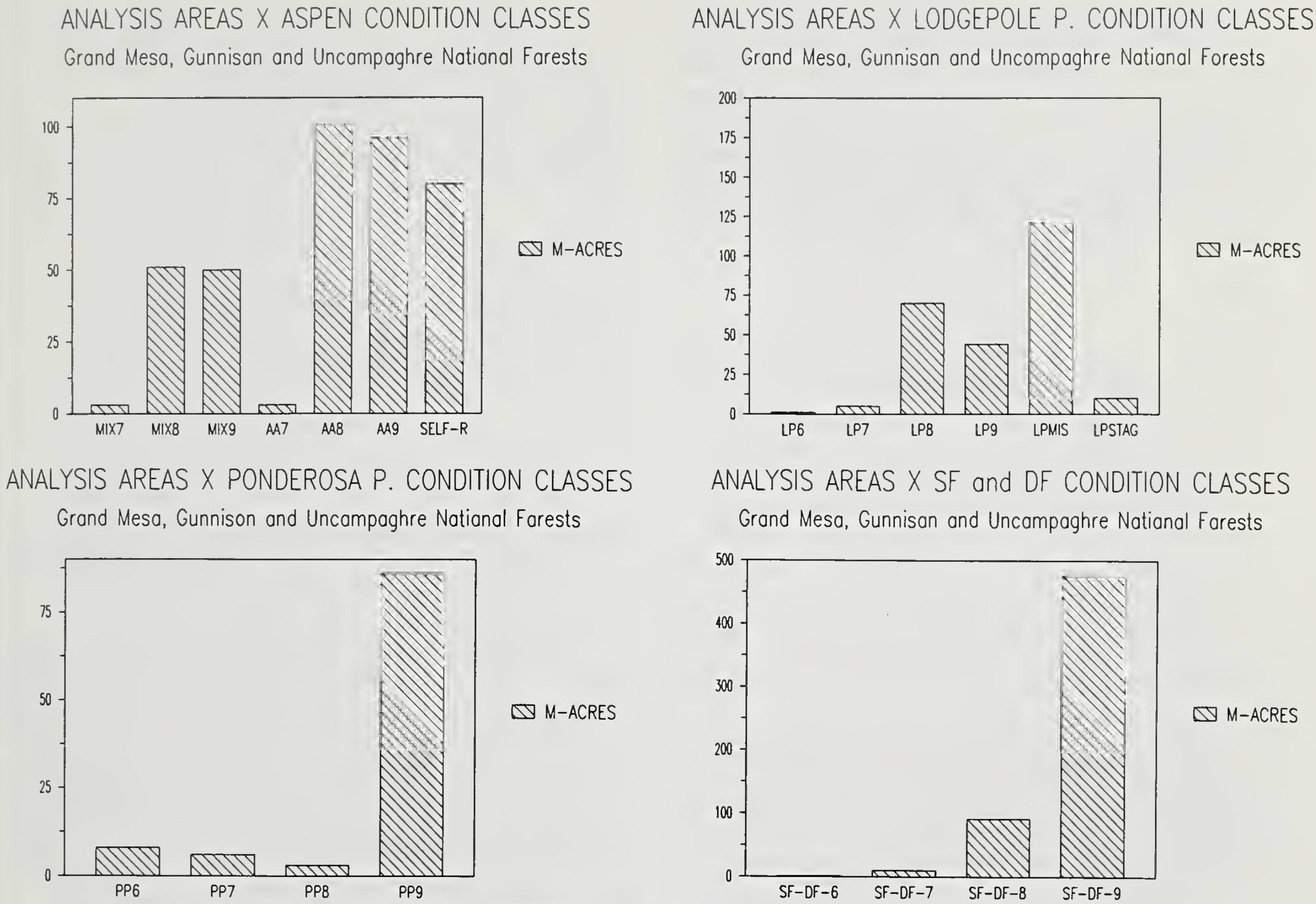


Figure 4.--Timber analysis areas.

The area generally will have a mosaic of fully stocked stands that follow natural patterns and avoid straight lines and geometric shapes. Management activities are not evident or remain visually subordinate along Forest arterial and collector roads and primary trails. In other portions of the area, management activities may dominate in foreground and middleground, but harmonize and blend with the natural setting.

Roaded-natural recreation opportunities are provided along Forest arterial and collector roads. Semi-primitive motorized recreation opportunities are provided on those local roads and trails that remain open.

Growth and yield models have to be flexible in order to simulate the different outputs expected from even-aged management versus uneven-aged management systems and thinning versus not thinning, etc. Sometimes models have to be applied that were not designed for a particular application. For example, even though RMYLD2 is an even-aged stand model, this uneven-aged system might be simulated with the assumption of even-aged groups.

Growth and Yield

The Forest Inventory field samples were stratified by timber analysis areas (timber type and condition class) to generate a single per acre stand table for each condition class. These provide the basic input for growth and yield models and the development of yield tables.

"Per acre yield tables will be developed for timber and other resources where the objective of vegetation treatment is to provide the associated multiple-use benefits. The yield tables represent production responses to management activities for such resources as range, timber, wildlife, recreation, and water" (Grand Mesa, Gunnison, and Uncompahgre, Draft Addendum to Planning Action 2, May 1987).

In general, R2GROW is used for older existing stands and RMYLD2 is used for regenerated stands or younger established stands. However this is not a "hard and fast" rule since sometimes RMYLD2 is used for mistletoe infected older existing stands, etc. Several different prescriptions and harvest methods may be modeled for each analysis area. Refer to figure 5 for a generalized flowchart of the use of growth and yield programs in the Rocky Mountain Region's forest planning process.

Each prescription for timber analysis areas is modeled using R2GROW or RMYLD2 to develop per acre yield tables for timber and other outputs to be used in FORPLAN (Forest Planning Model). The yield tables developed for the regenerated stands using RMYLD2 focused on the vegetation cover type since condition class is not as much of a factor for regenerated stands. A single regenerated stand table is used for several existing stand conditions. Refer to figure 6 for an example yield table generated by the RMYLD2 program.

Forplan

FORPLAN is the computer model that was used for the development of most of the current Forest Plans.

> "The Forest Planning Model (FORPLAN) will be the required primary analysis tool for the Forest Plans. The FORPLAN model is a linear programming package for resource allocation and activity scheduling, with linkages to program planning." (USFS Washington Office letter of December 3, 1979, file designation 1920).

Timber, range and other vegetation analysis areas are further refined by other identifiers relating to issues, concerns and opportunities prior to FORPLAN analysis:

> "Each analysis area will be defined by six levels of attributes with respective categories. Each land unit or site displayed in the resource date base (RIS) will be assigned to a specific analysis area based upon that land unit's unique characteristics. The analysis area acres are an aggregation of the acres of each land unit from the data base (RIS)." (Grand Mesa, Uncom-

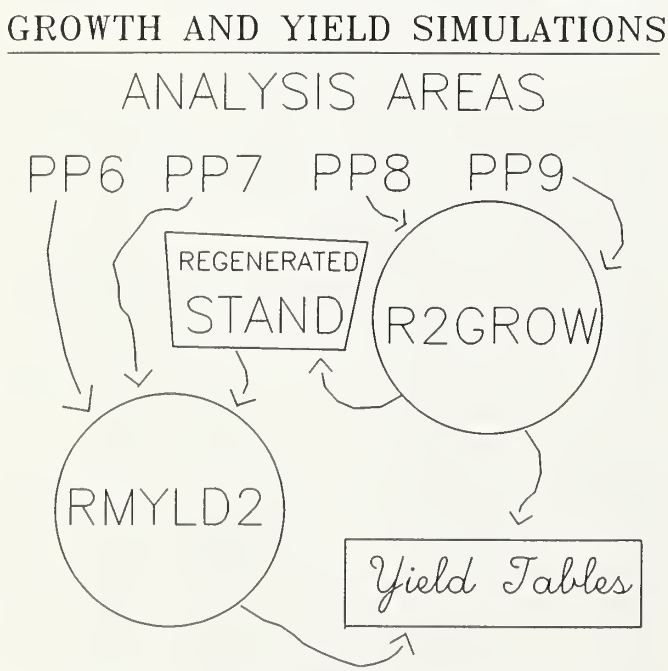


Figure 5.--Overview of the use of RMYLD2 and R2GROW for forest planning in the Rocky Mountain Region.

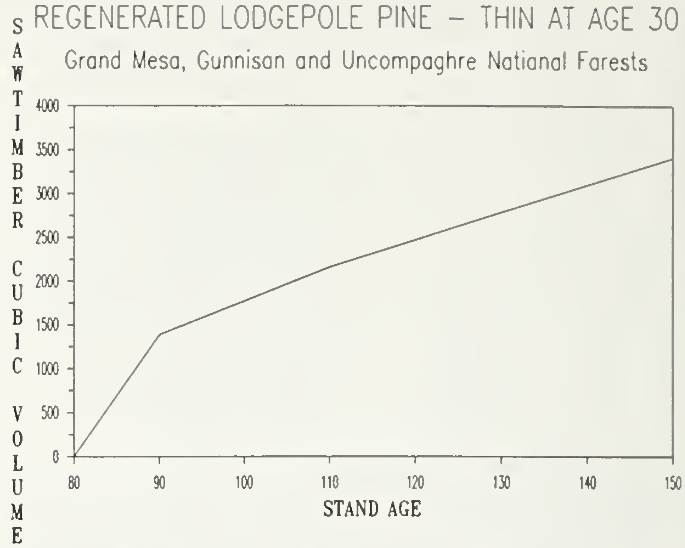


Figure 6.--Sample yield table generated by RMYLD2. Precommercial thinning and clearcut in the lodgepole pine forest type.

> pahgre, and Gunnison, Draft Addendum to Planning Action 2, May 1987)

The six levels of analysis area identifiers are Proclaimed Forest, understory condition of forage for livestock, slope class, road access, vegetation cover types, and vegetation condition class.

The following R2RIS data base components are considered necessary for the re-analysis and the ones flagged with and asterisk (*) were used to define FORPLAN analysis areas (Grand Mesa, Uncompahgre, and Gunnison, Draft Addendum to Planning Action 2, May 1987):

Component Name	Description
Location	Map and data base identifier
Site	Map and data base identifier
Area Acres	Area of each site (stand)
*Slope Percent	Describes the majority of site
Aspect	Direction the site faces
Elevation	To the nearest 100 feet
Watershed	Identifies watershed site is in
County	County site is located in
*Ownership	National Forest admin., etc.
*Land Use Class	Forest land, nonforest land, water
Special Kind	Wilderness, Non-Wilderness, etc.
Special Unit Codes	Big Blue Wilderness, etc.
Range Allotment	Range Allotment site is in
*Range Component	Range suitability and type
Timber Component	Timber suitability
Recreation Opportunity Spectrum	ROS Classes (inventoried)
Visual Quality Objective	VQO Classes (inventoried)
*Game Range Type	Summer & Winter Range
Other Site Types	Administrative Site, etc.
*Road Access Class	Miles
*Range Condition	Ecological Condition
*Range Trend	Ecological Trend
*Forest Type	Spruce/fir, Lodgepole Pine, etc.
*Stand Size Class	Sawtimber, poletimber, etc.
*Mistletoe	Mistletoe Infection Rating
*Forest Option Field	Forest Condition Classes

Forplan Outputs

Yield tables are used in the model depending upon prescriptions and alternatives selected by the model. The FORPLAN outputs mostly related to the growth and yield projections are Allowable Sale Quantity (ASQ), Long Term Sustained Yield Capacity (LTSYC) and the final suitable acres. ASQ is defined as follows:

> "The quantity of timber that may be sold from the area of suitable land covered by the Forest Plan for a time period specified by the plan. This allowable sale quantity (ASQ) is usually expressed on an annual basis as the average annual allowable sale quantity." (FSM 1900)

LTSYC is defined as follows:

> "The highest uniform wood yield from lands being managed for timber production that may be sustained, under a specified management intensity, consistent with multiple-use objectives." (36CFR 219.3)

> "... a quantity which can be removed from such forest annually in perpetuity on a sustained-yield basis ..." (National Forest Management Act of 1976)

Table 1 displays timber outputs for the current Forest Plans in the Rocky Mountain Region.

Project Planning

Projects plans are tiered to the Forest Plan and implemented based on the Forest Plan Implementation Schedule. Project plans are not another level of planning, but instead an extension of the Forest Planning Process with more detailed

Table 1.--Rocky Mountain Region forest plans.[1]

	Suitable Acres (M-acres)	Average Annual ASQ (MMCF)	ASQ (MMBF)	LTSYC (MMCF)	LTSYC (MMBF)
Arapaho/Roosevelt	360	7.4	28.4	16.2	62
Gm/Unc/Gun	476	7.0	35.0	21.0	105
Pike/San Isabel	582	7.6	25.7	12.8	43
Rio Grande	465	7.2	36.1	17.5	88
Routt	381	7.7	36.4	12.2	57
San Juan	470	10.2	40.7	19.2	77
White River	473	5.3	25.2	27.3	131
COLORADO	3207	52.4	227.5	126.2	563
Bighorn	266	3.9	15.1	7.6	29
Black Hills	1034	35.1	152.1	40.0	173
Medicine Bow	448	5.9	28.4	16.9	81
Shoshone	86	2.5	11.2	3.5	15
WYO./S. DAK.	1834	47.4	206.8	68.0	298
REGION 2	5041	99.8	434.3	194.2	861

[1]"Forest Plan Timber Facts," U.S. Forest Service, Rocky Mountain Region, April 8, 1987.

PROJECT PLANNING

FOREST PLAN

IMPLEMENTATION SCHEDULE

INVENTORY

(R2RIS STAND EXAM)

ANALYSIS AREAS

ALTERNATIVES

OUTPUTS

(SIMULATIONS OR CANNED)

ENVIRONMENTAL ANALYSIS

Figure 7.--Overview of the use of growth and yield models for project planning in the Rocky Mountain Region.

site specific data available for the project area in consideration.

Even though more data is available, growth and yield simulations are generally not done to the level of precision that they were for the Forest Plans. Often, "canned" growth and yield simulations are referred to such as the "Book Process" (Managing Forested Lands For Wildlife, Colorado Division of Wildlife, 1984), or runs previously made representing various condition classes on a District or Forest.

In any case, alternatives are tested and outputs are based on current or past growth simulations and an Environmental Analysis is always made which will result in one of three documents:

1. Environmental Impact Statement
2. Environmental Assessment
3. Categorical Exclusion

Refer to figure 7 for a diagram of the project planning process.

Growth and Yield System Needs

The existing growth and yield models have been used for the current round of Forest Planning, but are weak in many areas (fig. 8). RMYLD2 cannot simulate uneven-aged stand structures, mixed species stands or long rotation ages. In addition, it is difficult to match the inventory of existing stands using RMYLD2. R2GROW cannot handle mixed species stands or long rotation ages, and is not capable of simulating regenerated stands. R2GROW also lacks research validation and is currently out-dated.

For the future, we need a complete growth and yield system for the Rocky Mountain Region (Region 2 & Rocky Mountain Station Forest Growth and Yield System Development and Implementation Plan, February 13, 1985). This plan includes phasing out R2GROW and replacing it with a new model built by the Rocky Mountain Forest and Range Experiment Station. This new model will be a Generalized Growth and Yield Model (GENGYM). GENGYM is proposed to be a 1-inch diameter class model designed to simulate growth and yield of even-aged, uneven-aged, and irregular structured forest stands of pure or mixed species composition.

RMYLD2 is expected to still have use in the future since it is a whole stand model and is more economical and efficient than a diameter class or individual tree model for some applications. In addition, RMYLD2 simulations can be made based on data that is stored in the R2RIS data base. Data requirements for diameter class (e.g. GENGYM) or individual tree models (e.g. PROGNOSIS) require the use of tree data files (Forest Inventory Field Sample Data).

Refer to figure 9 for a summary of the Rocky Mountain Region needs for a complete growth and yield system that will handle mixed species and uneven-aged management.

One of the needs listed is to monitor the results of models; "Do we really get the expected results from thinning that were simulated?" Where thinning occurs will be tracked in the R2RIS data base. However, a monitoring plan for the expected growth increases, mortality losses, etc. for planned treatments has not been designed for the region. This would probably involve the use of permanent plots established in areas before and after treatments which are expensive. We have the tools to measure many types of permanent plots and store data, but they are currently being utilized for continuous inventory samples which are not established to reflect various treatments.

Summary

Growth and Yield models play an important role in the Forest and Project Planning Process. Without them various prescriptions and alternatives cannot be adequately tested. Many of the alternative outputs in the development of the Forest Plan are directly related to the models such as Allowable Sale Quantities, or Long Term Sustained Yield Capacities.

There is still a long way to go in the development of models. Model results have not been monitored, current models do not display statistical variances for each simulation period, and most models are weak in estimating mortality. Before models are used to any great extent for Project Planning they will have to become more "user friendly." Most current models were built for the Fort Collins Univac Computer.

LIMITATIONS OF EXISTING MODELS

RMYLD2
(Whole Stand Model)

— Unevenaged Stand Structures

— Mixed Species Stands

— Long Rotation Ages

— Match Existing Stand Inventory

R2GROW
(Diameter Class Model)

— Mixed Species Stands

— Long Rotation Ages

— Regenerated Stands

— Research Validation

Figure 8.--Limitations of R2GROW and RMYLD2.

GROWTH AND YIELD SYSTEM NEEDS

Capability to Project the Development of Stands in All Forest Cover Types

Provision for Updating Existing Inventories

Simulation of Both Even and Unevenaged Silvicultural Systems

Simulation of No Action as Well as Applicable Management Alternatives

Simulation of Natural, Noncatastrophic Mortality, Bark Beetle Mortality, and Growth Loss from Defoliation and Diseases

Accounts for Establishment of Natural Regeneration

Simulation of Either Individual Stands or Stratum Averages

Compatibility with Stand Data Collection and Printout

Allow for Different Merchantability Standards

Provide Linkage to Other Output Models

Monitoring

Figure 9.--Rocky Mountain Region needs for a complete growth and yield system.

For systems to be responsive to the needs of District Foresters they need to be re-written for the Data General Computers (DG) currently installed in District Offices or for personal computers (PC).

The RMYLD2 program has been modified to run on a "Personal IBM compatible computer" or the "Data General Computer" by the Rocky Mountain Forest and Range Experiment Station. GENGYM will be developed strictly for the "DG" or "PC." It is expected that this is the direction growth and yield models will take in the future.

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Trees--The Link Between Silviculture and Hydrology

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Water and timber are forest products that result from complex processes at the watershed, stand, and tree levels. Subalpine forest ecosystems, which are considered here to be equivalent to stands or small catchments, receive inputs of energy, carbon, water, and nutrients. Within the ecosystem, a wide array of processes involves conversions and exchange of these components. The net result of these processes and transformations affects the quantity of water available for streamflow and biomass production, including merchantable bole volume.

The study of processes involved in water and biomass production from subalpine forest ecosystems often requires research on isolated components of the ecosystem. Yet, an understanding of ecosystem behavior also requires that all the components be considered together, because all of the processes and components of the ecosystem interact to produce the observed outputs.

Trees play a crucial role in ecosystem behavior, because a major portion of energy, carbon, water, and nutrient exchange in ecosystems are influenced by or occur in trees. At the level of forest stands, for example, the canopy intercepts energy and influences air movement, thereby affecting photosynthesis, transpiration, and the thermal and light environment of the forest stand. An existing stand represents the current status of competition for energy, water, and nutrients.

At the level of foliage, carbon is fixed by photosynthesis, some of it stored in wood or other portions of the biomass until harvest or death, some utilized for foliage or fine roots having a shorter lifetime than that of the tree, and some utilized in respiration. Also in foliage, water absorbed by tree roots is transpired and returned to the atmosphere as vapor. And finally, nutrients continually are absorbed and used for growth or returned back to the forest floor by foliar leaching or loss of plant tissue.

The gas exchange processes of the foliage provide one link between silvicultural and hydrologic phenomena. CO_2 enters foliage through stomata, and water leaves the foliage through the same stomata (fig. 1). Thus, dry matter production, the essence of timber productivity, and transpiration, a major component of the hydrologic cycle, are simultaneously dependent on stomatal behavior. This paper focuses on how trees influence various aspects of the water and carbon cycles, and discusses how tree processes are involved in subalpine forest hydrology and silviculture.

Papers by Smith, Meiman, and Troendle and Kaufmann (this volume) discuss related aspects of silviculture and hydrology of subalpine forests in the central Rocky Mountains. Stottlemyer addresses the trends in input/output chemical balances of the Fraser Experimental Forest watersheds.

TREES AND THE CARBON CYCLE

Carbon fixation by trees is the sole source of dry matter for wood production, except for very minor amounts of nutrients found in woody material. While photosynthesis by the understory vegetation may be substantial in some forest types and may be important in forage production, it does not contribute to commercial wood production.

Carbon fixation depends upon a number of factors. There is reasonably good evidence that, for young stands, biomass productivity is nearly linearly related to interception of radiation (Linder 1985). Radiation interception is dependent on day length, slope and aspect, shading by competing vegetation, and the arrangement of foliage within a crown. For a given physiographic location, optimal stand productivity depends upon the canopy being configured in a way that maximizes light interception while guarding against the negative effects of over-crowding, which may lead to carbon allocation away from harvestable product. Silvicultural research (e.g., Alexander 1986a, 1986b; Alexander and Edminster 1980, 1981) has been conducted to maximize timber productivity using an empirical approach to density control that effectively optimizes radiation interception for a given site.

The volume growth of a tree depends not only upon how much energy the tree crown captures and upon factors affecting photosynthesis through effects on stomatal behavior, but also on the allocation of the newly fixed carbon. Within trees, carbon may be allocated to stem dry matter production, replacement of foliage and fine roots, or maintenance respiration. The "harvest index," the proportion of stemwood to total tree biomass, is one measure of long-term effects of annual carbon allocation. Waring and Schlesinger (1985)

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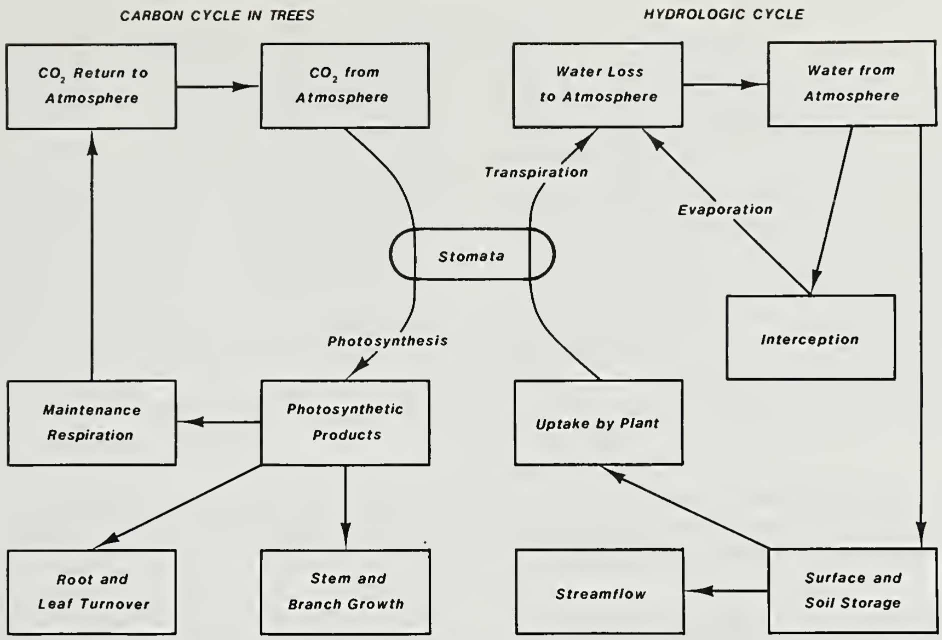

Figure 1.--Simplified carbon and hydrologic cycles. Photosynthesis and transpiration involve the exchange of CO_2 and water vapor through stomata.

hypothesize that there is a hierarchy of priority for receiving newly fixed carbon, and stemwood is generally produced only after demands by foliage and fine roots have been met. An understanding of allocation processes therefore may help determine how management practices can alter the harvest index.

Kaufmann and Ryan (1986) examined the growth rate of individual subalpine conifer trees. They determined that volume growth is influenced by energy capture, which is a function of leaf area, but concluded that other factors also were important. Their data showed that the growth efficiency of trees (volume growth per unit absorbed radiation) was different among species and varied with tree age. Efficiency was notably different between lodgepole pine, an intolerant species, and Engelmann spruce and subalpine fir, both tolerant species (fig. 2; also see Ryan, this volume). The growth efficiency of pine was much higher during the first 100 years than that for spruce and fir, but it declined to the spruce-fir levels in about 200 years.

It may be hypothesized that tree volume growth and growth efficiency depend, in part, upon the amount of new photosynthate that is utilized in maintenance respiration, and that the maintenance respiration requirements depend on the respiratory biomass existing in the tree. Ryan (this volume) reports that the amount of sapwood supported per unit leaf area varies among species, and he is currently conducting studies on the sapwood respiration rates of pine and spruce of varying sizes and ages. These studies may be helpful in reaching an understanding of the balance and allocation of carbon in subalpine conifers, and they may provide a basis for evaluating limitations of growth caused by inadequate water or nutrient availability.

There is increasing evidence (Grier et al. 1981, 1982; Linder and Axelson 1982) that fine root production represents a major sink for newly fixed carbon. Fine roots (including fungal symbionts) are very important for both water and nutrient uptake, and aboveground production may depend more on how such carbon is used by fine roots than on differences in assimilation. Thus, silvicultural practices, such as thinning and fertilization, may increase the harvest index because of decreased allocation to fine root production rather than increasing net assimilation.

Current empirical prediction models provide estimates of timber and water production on a par with our present ability to measure them. While empiricisms are seldom the best possible estimators of tree or stand performance and interaction, estimators specific to each microprocess within a tree are likely to involve too much inherent variability for accurate prediction when aggregated to a stand level. Knowledge of carbon balance and carbon allocation in subalpine species is very limited, however. Additional research on the carbon cycle in subalpine trees may refine our understanding of the effects of stand structure, site, and environmental conditions on tree growth. Enhanced knowledge of these microprocesses within the tree and their effect on macroprocesses within the ecosystem will certainly provide guidance to improve predictive relationships at the tree and stand level.

TREES AND THE HYDROLOGIC CYCLE

The hydrologic cycle of an ecosystem includes water input as precipitation (snow or rain), movement within the ecosystem (often involving a change of phase from snow to liquid water and from liquid to vapor), and output in the forms of

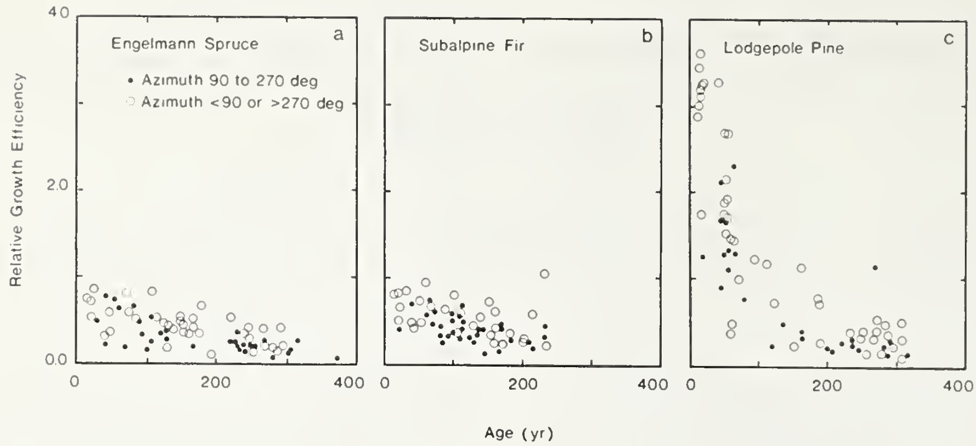

Figure 2.--Relative growth efficiency as a function of tree age and aspect of the site for (a) Engelmann spruce, (b) subalpine fir, and (c) lodgepole pine. The relative growth efficiency is a measure of tree volume growth in relation to potential absorbed radiation.

water (streamflow) or water vapor (evapotranspiration or ET). Associated with the movement of water is the movement of chemicals, both those entering and leaving the ecosystem and those cycling within the ecosystem. Trees absorb water and nutrients from the soil. Through transpiration they release water to the atmosphere, and through foliage leaching and foliage and root turnover they release some nutrients to the soil and litter. Trees also intercept significant quantities of water that evaporates without entering the soil-plant system, and they intercept chemicals from the atmosphere, both in precipitation and as dryfall.

Streamflow from forested ecosystems depends upon the total precipitation received and the amount lost from the unit as ET, plus any amount that percolates directly into the groundwater supply. Trees have a direct influence over the amount of precipitation input available for streamflow, because they (1) transpire water, (2) intercept water that is evaporated or sublimated directly back to the atmosphere, and (3) modify the understory ET environment.

Water yield from subalpine forests in the central Rocky Mountains is very important in the West, and considerable attention has been given to the effects of stand management on water yield from subalpine watersheds. Many studies have indicated that the annual yield of water may be increased by stand manipulation. Three watershed experiments in Colorado have demonstrated increased water yield after harvest (Wagon Wheel Gap, Fool Creek, and Deadhorse Creek--see Troendle 1983). The Fool Creek experiment continues to demonstrate increased streamflow more than 30 years after harvest. Furthermore, calculations based on time-series analysis of the decline in increased streamflow, on the decline in winter snowpack accumulation, and on projected increases in tree leaf area index (LAI) in the harvested areas, all indicate that the increase will not totally disappear (return to pretreatment streamflow) until 70 to 80 years after harvest (Kaufmann 1985a, Troendle 1983, Troendle and King 1985).

Most effects of stand manipulation on water yield may be attributed to effects on total annual ET, because the gross annual precipitation and percolation to groundwater (if any) are not likely to be affected by stand density. In a review of the use of forest management techniques to increase the yield of water from subalpine forests, Troendle (1983) provided evidence indicating that water yield augmentation resulted from stand harvesting effects on both summer ET and winter snowpack accumulation. Meiman (this volume) reviews evidence that the snowpack water equivalent in harvested watersheds is increased because of a reduction in sublimation when stands are thinned or clearcut. Troendle and Kaufmann (this volume) address the effect of stand density on both total annual water yield and on growing season soil water depletion rates.

Annual ET of subalpine forests has several components. Variation in these components through the year and as a result of stand manipulation makes ET both dynamic and very complex. During the summer months when no snow exists, stand ET includes overstory transpiration, understory transpiration, and evaporation of water intercepted by the vegetation and the litter and soil. During the winter, stand ET is composed primarily of evaporation from the snowpack and evaporation of snow intercepted by the forest canopy. The generally frozen conditions prevent transpiration by the trees. During the transition periods of spring and autumn, transpiration by the overstory varies widely with weather conditions. Snow cover during these periods is incomplete or transient, and ET beneath the overstory occurs as evaporation from the snowpack and litter, transpiration from the understory vegetation, or both. Interception losses during this period include evaporation of both rain and snow.

Summer ET

The principal pathways of water loss for the overstory, understory, and ground are shown in figure 3. Each compo-

nent of summer ET is influenced by the type and structure of the forest stand occupying a site. Most evidence suggests that during summer months, ET in the subalpine forest exceeds precipitation and results in a moderate soil water deficit. Troendle (1987) recently showed that in an uncut area, soil water depletion exceeded summer precipitation, resulting in soil water deficits. Flow into a subsurface collection system at the base of a forested slope occurred only in the spring after snowmelt satisfied recharge requirements. Recharge requirements on a nearby clearcut plot were substantially less. Subsurface outflow from the clearcut occurred after a significant summer rainfall or in early autumn when ET was reduced, indicating that 1% or 2% of the summer rainfall may directly become streamflow following timber harvest.

These results illustrate the importance of the forest canopy in affecting summer ET. A forested site utilized both summer precipitation and some of the water stored in the soil, resulting in soil water depletion during the summer months. In an unforested site, however, the understory vegetation utilized much less of the stored soil water, resulting in a 2.5- to 3-inch (6- to 8-cm) reduction in soil water depletion. This allowed large storms during the summer and precipitation in the autumn (when ET demands were lower) to create a surplus, resulting in outflow from the clearcut. Since more than 95% of the measured flow increases occur during the spring snowmelt period, the subtle growing season changes observed at the plot level are not easily detected at the watershed level. However, Troendle and Leaf (1980) noted that flow increases can occur any time precipitation input (rain or snowmelt) exceeds the recharge requirements in the cutover area (also addressed in Troendle 1983).

Overstory Transpiration

Overstory transpiration is directly related to the atmospheric evaporative demand, but it also is influenced by LAI and stomatal behavior (Kaufmann 1984a, Kaufmann and Kelliher in press). At equivalent stand basal areas, LAI varies greatly depending on the species composition of the stand (Kaufmann et al. 1982). Furthermore, stomatal behavior also varies among species, such that for equivalent environmental conditions and basal areas, stands of different species may have widely different tree transpiration rates (Kaufmann 1985b). Physiographic characteristics of the site (slope, aspect, and elevation) also influence overstory transpiration through effects on light, temperature, and humidity within the forest canopy.

Understory ET

Overstory stand density and species composition also may affect understory ET. Differences in transmission of irradiance by the overstory affect how much energy is available at the forest floor for understory ET. Light transmission of subalpine forest stands is a function both of LAI and of leaf area clumping within crowns (unpublished data, Oker-Blom, Ryan, and Kaufmann). At equal stand densities, the LAI for lodgepole pine and aspen stands is considerably lower than for Engelmann spruce-subalpine fir stands. Differences in light transmission to the forest floor may influence the understory species composition and vegetation density, as well as the environmental conditions regulating ET.

Overstory density and structure affect aerodynamic mixing in the forest stand, and this may affect ET processes. Most

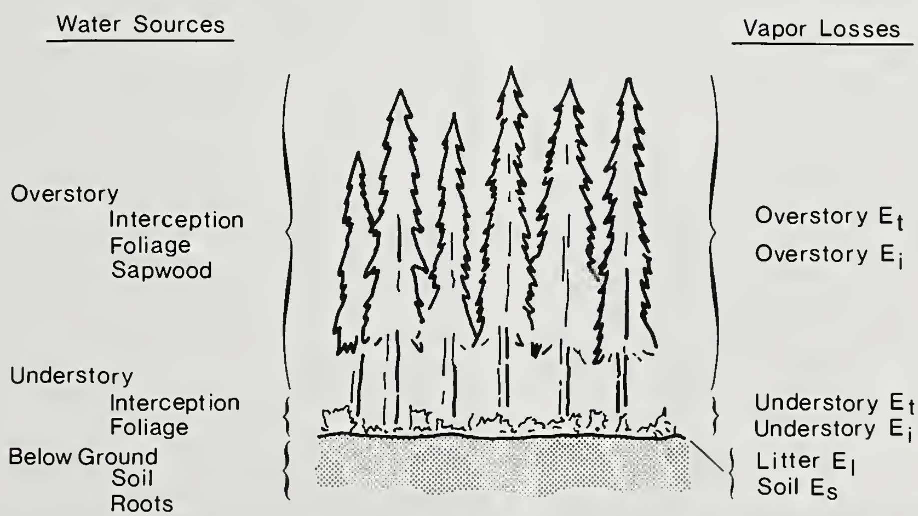

Figure 3.--Water sources and avenues by which water vapor is lost from a forest. Evapotranspiration (shown here as E) may occur through transpiration (subscript t) from the overstory and understory vegetation, through evaporation of intercepted water (subscript i), and through evaporation from litter and soil (subscripts l and s).

evidence suggests that air in the overstory of conifer stands is well mixed, and as a result transpiration is regulated primarily by stomata and the vapor gradient (Jarvis 1985, Kaufmann and Kelliher in press). Lower in the canopy, however, mixing is poorer. As a result, the microenvironmental conditions existing at the understory level depend much more on the radiation environment than they do in the overstory. This is evidenced by the much warmer temperatures of air and soil on south-facing slopes than on north-facing slopes during midday (Noble and Alexander 1977), even though canopy temperatures of the overstory seem to be relatively unaffected by radiation input (Kaufmann 1984b). Furthermore, canopy density and the related aerodynamic mixing may differ with aspect, with north aspects typically having a more dense overstory than south aspects.

As a consequence of these overstory effects on the distribution of radiation and on aerodynamic mixing, the density and structure of the overstory may play an important role not only in affecting overstory transpiration, but also in regulating understory ET. While data are not available, it is quite possible that tree harvesting techniques that result in different patterns of leaf area distribution in the overstory (i.e., partial harvest versus patch cutting) could alter understory ET even though they result in the same total residual stand LAI.

Interception

Rainfall interception by the overstory is affected by the size and duration of storm events, but interception depends as well upon the surface area on which water can accumulate. Wilm and Dunford (1948) measured precipitation in openings and beneath lodgepole pine stands of varying density and observed interception losses by the overstory of 7% to 32% of precipitation during July, August, and September. Reynolds and Knight (1973) observed that throughfall was 79% of precipitation for four lodgepole pine stands, compared with 60% for four spruce-fir stands (equivalent to interception rates of 21% and 40%). Interception in both of these studies appeared to be positively correlated with LAI.

Interception by the understory and litter also prevents rainfall from reaching the rooting zone of the trees. Reynolds and Knight (1973) observed that the water-holding capacity of litter was about 125% of the litter dry weight in both lodgepole pine and spruce-fir types. It also is possible that, in harsh sites where mineral soil is exposed, intercepted water in the upper few centimeters of soil may be unavailable to trees because the absorbing roots are deeper under these conditions.

Off-Setting Conditions

It is clear from this discussion that a number of factors, which may vary naturally or as a result of management activities, can affect the ET processes occurring during the transpiration season. It also is obvious that changes in stand structure and composition may have complex effects on ET, because several components of ET may be changed.

Considering overstory transpiration alone, transpiration apparently is affected by LAI, and it varies widely among species at the same stand basal areas (Kaufmann 1984c, 1985b). But within a species, a change in stand density and LAI influences interception of precipitation by the overstory, the transmission of light to the understory, and perhaps water availability for growth and transpiration by understory vegetation. Similarly, the differences in LAI among species at similar stand densities may affect interception and understory ET processes.

For example, the understory vegetation beneath spruce-fir stands is often fairly sparse, whereas beneath aspen stands the vegetation is frequently dense and lush. Estimated branch transpiration rates for aspen were considerably lower that those for spruce-fir, suggesting that less soil water was extracted by aspen than by spruce-fir (Kaufmann 1985b). However, the aspen measured were in mixed stands rather than in pure stands. In pure stands, a well-developed aspen understory may use considerably more water in ET than a spruce-fir understory because of higher light transmission, better development of the vegetation, and higher availability of soil water. Consequently, some of the savings by the aspen overstory may be offset by increased losses from the understory. Limited data from the Fraser Experimental Forest indicate soil water depletion rates under various densities of aspen are similar to those under similar densities of lodgepole pine.

As another example of the complexity of relating total ET to stand conditions, a reduction in basal area by partial harvest versus patch cutting may be considered. When LAI is reduced over an entire stand by uniformly distributed tree harvesting, light transmission to the forest floor increases, favoring increased ET from the forest floor. In a clearing created by removal of the same basal area in patches, the exposed forest floor receives the entire radiation input and probably has higher aerodynamic mixing, thereby favoring substantially increased ET than for the understory vegetation in the uncut portion of the stand or in the partially harvested stand. In addition, changes in the amount of understory vegetation may influence the relative losses from transpiration and evaporation from the forest floor or clearcut. The net effect of these differences on total ET of the two stands is not known.

Research is being conducted on each component of ET, with the goal of developing and testing techniques for estimating the ET components independently. If successful, this research will provide methods for assessing how total ET may be manipulated through stand treatment. Furthermore, this research may bring us closer to the ability to estimate each term of the hydrologic cycle independently without obtaining any component by difference ("closure"), and it may facilitate relating summer hydrologic processes to processes important in tree ecophysiology and in nutrient cycling.

Winter ET

Winter water vapor losses do not appear to be as complex as summer ET losses, although they are not well understood. Winter losses in subalpine forests are primarily through sublimation of intercepted snow (or evaporation of snow meltwater on branches if air temperatures are warm enough) and sublimation of the snowpack. Transpiration of trees is negligible during winter months because of stomatal inactivity and freezing conditions in the soil-plant system.

Data summarized by Meiman (this volume) indicate that snowpack water equivalent can be linearly increased up to 30% or more as basal area is reduced, and a significant portion of the annual increase in water yield associated with timber harvest is related to the associated reduction in interception loss. Consequently, LAI and the spatial distribution of foliage in trees and stands influence winter interception and evaporation in much the same way they affect summer interception and ET. Effects on snowpack evaporation are not well understood, but it has been shown that energy input through air movement and, to a lesser degree, solar radiation influence winter evaporative rates in much the same way they are presumed to affect understory ET during the summer.

SUMMARY COMMENT

All aspects of forest management, for whatever intended purpose, and all aspects of forest ecosystem behavior center on trees as the main biological unit and on stands as the organizational structure within which they function. Complex and dynamic silvicultural and hydrologic processes are thereby linked at the stand and tree level. An understanding of these processes may be helpful in forest management and in assessment of subalpine forest ecosystem function. Continued research on tree and stand behavior will increase our understanding of all the biological and physical implications of stand management and environmental change.

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245 # Influence of Forests on Snowpack Accumulation

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Abstract--There is ample evidence that both small patch cuts and thinning increase snow accumulation in the treated area. These effects extend well beyond the approximately 50 years of record at the Fraser Experimental Forest. The processes responsible are not yet precisely defined, but reduced snow interception losses appear to be a major factor. There is no evidence from recent studies at Fraser of significant redistribution from forests to openings during between storm intervals.

In the subalpine forests snow is the major source of water supply and an important ecological factor. Thus a better understanding of the processes that influence the accumulation, redistribution and ablation of the snow cover is essential for effective management of subalpine forests. This paper focuses on the influence of forests on snowpack accumulation. Other factors that influence snowpack accumulation include climate, topography and nonforest vegetation. Although a brief review of literature on related studies is given, the emphasis is on the work at the Fraser Experimental Forest where the author has worked in association with the US Forest Service over the past 20 years.

Studies Related to Fraser Experimental Forest

Among the earliest recorded observations in the United States on the influence of forests on snow accumulation were those made by Carpenter (1901), Church (1912), Jaenicke and Foerster (1915) and Betts (1916). The most graphic description was given by Church who described the ideal forest for snow accumulation as resembling a giant honeycomb, the glades of the forest representing the cells of the comb.

Miller (1964 and 1966) presented two comprehensive reviews of interception processes and transport of intercepted snow during snowstorms. In these reviews Miller discussed the factors influencing the adhesion of snow on foliage temperature, wind and characteristics of the obstacles; and the factors influencing cohesion of snow atmospheric and crown conditions. Processes involved in transport of intercepted snow from tress included snow sliding from branches, stem flow and dripping of melt water, vapor transport from melt water and snow and removal of snow by wind. These two publications provide an excellent set of references on snow interception processes.

Meiman (1970) reviewed approximately 70 North American studies on snow accumulation in relation to elevation, aspect and forest canopy with emphasis on the subalpine and montane zones. This review illustrated that although elevation has a greater effect on snow accumulation on a large scale, forest canopy can have a dramatic effect over very small distances. Among the studies reviewed that attempted to give a quantitative relationship between snowpack water equivalent and canopy density, Packer (1962) reported a 0.42 inch increase per 10 percent decrease in canopy, Lull and Rushmore (1960) indicated a value of 0.33 inches, and Kittredge gave values ranging from 0.50 inches to 2.2 inches.

The study by Gary (1974) of snow accumulation as influenced by a small clearing in a lodgepole pine forest is relevant to the Fraser Experimental Forest work because it was located in an area with similar climate and stand conditions. He found an increase of approximately 24 percent in peak snow water equivalent in a one tree height wide (1H) clearing. Further, he found the excess water equivalent in the opening was nearly equal to the deficit in the leeward forest zone. The author commented that he could only conjecture as to the processes responsible for the greater accumulation in the clearing. Among the processes discussed were backeddies of the airstream during storms and/or redistribution from the leeward forest border during or following storms. An alternate hypothesis was that the greater snow in the clearing was offset partly by greater loss by vaporization in the sun exposed lee forest. The author did not discuss reduced interception loss as a possible cause of the increase.

In a follow up study Gary (1980) increased the width of the 1H clearcut to 3H and 5H in consecutive cuttings. The width

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extension was done on the lee side of the original cut. Data for 10 winters indicated an average net loss of 6.5 percent for all widths when the volume of snow in the opening plus that in the lee forest was compared with the upwind forest even though there was 20 to 48 percent greater snow accumulation in the openings. Sublimation and wind transport outside the plot (i.e. into the lee forest beyond the measured area) were thought to account for the loss. For two of the ten years, barriers were constructed along the lee side of the 3H opening. For the 1974 snow year a belt of small (5-1/4-foot) lodgepole trees was erected along the lee border of the cut area. For the 1978 winter a 12-1/2-foot wood snow fence (40 to 50 percent density) was used. Placement of the barriers did not change the expected pattern of snow accumulation inside the clearing but snow catch along the lee side of the clearing and lee forest border was greatly altered. The fence was more effective than the trees and resulted in a 13 percent net snow increase on the study plot (opening plus lee forest). The barriers provided evidence that considerable amounts of snow are transported away from the lee forest border by wind action.

A set of studies in Canada (Golding and Swanson, 1986) have particular relevance to Fraser studies. At the James River study area, 60 miles northwest of Calgary, Alberta, the authors reported a spatially preferential loss from the snowpack in different sectors within forest clearings. The implication from this study is that differential ablation during the accumulation period can be an important factor in evaluating differences in snowpack accumulation in forest openings. At the James River study site snow water equivalent in 1/4H to 6H circular clearings ranged from 13 to 45 percent greater than in the forest and was reported to be "probably" a result of a combination of interception and redistribution.

At the Marmot Creek experimental watershed 24 miles SE of Banff, Alberta, clearings on two subbasin clearings were studied Twin and Cabin. On the Twin subbasin, clearings of 3/4 to 1-1/4H had 28 percent greater snow water equivalent than the intervening forest which the authors reported "seemed" to be the result of redistribution because the increase in the clearings just balances the decrease in the forest (based on an calibration with separate control area). On the Cabin subbasin the 20 to 32 acre blocks averaged 20 percent greater snow water equivalent than the forest and there was no evidence of redistribution of snow. The authors suggest that the increase is the result of elimination of interception.

These studies illustrate the complexity and frustration of trying to separate the interception redistribution ablation effects on snow accumulation and, as the authors indicate, ". . . the data do not provide definitive answers concerning the source of increased snow water equivalent in forest clearings."

Gary and Watkins (1985) reported on the effects of thinning a lodgepole pine stand in Wyoming at an elevation of 9000 feet. The thinned area had a lodgepole stand of 10,000 stems/acre before thinning and was thinned to a density of about 850 trees/acre with a basal area of 70 ft2/acre. The remaining trees had an average diameter of 4 inches and an average height of 30 feet. Comparison with a control area before and after thinning indicated a peak snow water equivalent increase of 2 inches or approximately 30 percent.

Fraser Studies

Wilm and Dunford (1948) reported the first comprehensive snow accumulation studies at Fraser. Twenty harvest cutting plots were established in 1938. The five acre plots were in mature lodgepole pine (Pinus contorta) intermixed with Engelmann spruce (Picea engelmannii) and alpine fir (Abies lasiocarpa). The stand contained 300 to 400 trees per acre larger than 3-1/2 inches d.b.h. with a height range for most of these trees between 35 and 85 feet. The merchantable timber volume (trees larger than 9-1/2 inches d.b.h.) averaged 12,000 board feet per acre. These stands were at an elevation of 9150 to 9700 feet. The experiment was designed to place four treated and one control plot in each of four randomized blocks. In 1940 all trees larger than 9-1/2 inches d.b.h. were removed from one plot in each block; three other plots were cut to a residual stand of 2000, 4000 and 6000 board feet of merchantable volume per acre.

In order to determine the effects of timber cutting on snow storage, 25 sampling points were established in each plot. Snow water equivalent was measured with a Utah snow sampler and weighed with a balance to 0.1 ounce between March 15 and April 1. These measurements were taken in 1938 and 1939 before cutting and in 1941 to 1943 after cutting in 1940.

The after harvest values as adjusted by Wilm and Dunford are presented in table 1. These values were calculated by covariance analysis used to adjust for aspect and yearly snowfall differences. Thus the heaviest cutting resulted in a net gain of 1.99 inches or 26 percent over the uncut plots. Snow accumulation increased in relation to intensity of cut. In presenting these results on snow accumulation, the investigators wrote as follows:

> The smallest quantities were observed under clumps of trees, and the largest quantities in the largest available canopy openings, about 60 feet in diameter. These observations provide a graphic clue to the probable effect of timber cutting on snow storage, because such treatments would increase the number and size of openings in the forest, and hence it should increase the average amount of stored snow.

Another important finding came from these early studies. On one half of each cut plot a minor timber stand improvement

Table 1.--Initial snow storage as a result of timber cutting (Wilm and Dunford 1948).

Treatment	Inches of water
11,900 f.b.m. uncut	7.60
6,000 f.b.m. residual stand	8.41
4,000 f.b.m. residual stand	8.61
2,000 f.b.m. residual stand	9.09
0 f.b.m. residual stand	9.59

was made by removing undesirable trees within the diameter range from 3.6 through 9.5 inches. The number of trees removed averaged 56 per acre. This treatment resulted in an average increase of 0.46 inches in snow accumulation or about a 5 percent gain.

In addition to comparing the initial snow storage (i.e. snowpack accumulation as of March 15 April 1), a comparison was made of net spring precipitation (mostly snow) during the period from March 15 April 1 to June 30 by using nonrecording rain gages on each of the plots for the years 1941 to 1943. These results from Wilm and Dunford are presented in table 2. Wilm and Dunford made several salient observations on the spring period results pointing out that about four fifths as much water was supplied by this source as by stored winter snow, and that the percentage increases resulting from heavy cutting were very similar to those found for winter snow storage.

Although Wilm and Dunford did not specifically mention the cause of the increased snow accumulation in their original work, later interpretation by Goodell and Wilm (1955) attributed it to the elimination of evaporation losses from snow intercepted on tree crowns.

Hoover and Leaf (1966) summarized much of their observations on snow interception at Fraser. Based on photographic records during the 1963 and 1964 snow season and long term measurements on Fool Creek, they inferred that snow redistribution could be a major factor causing differential snow deposition. This inference was based on their observations that snow remained on trees a relatively short time at their observation site near the Fraser Experimental Station headquarters, that the analysis at that time indicated no overall increased snow accumulation on the Fool Creek Watershed as a result of cutting, and that, despite considerable regrowth of young trees on the clear cut and heavily thinned plots of Wilm and Dunford, the ratio of treated to uncut plots had changed little if any. In concluding, the authors emphasized the extremely complex series of processes related to the accumulation and disposition of intercepted snow and called for additional studies on the aerodynamic processes involving transport of snow through and from the forest canopy.

Clearcut Studies

The Fool Creek watershed has been an important source of information on snow accumulation. This data was summarized most recently by Troendle and King (1985). The Fool Creek gage was constructed in 1941; the East St Louis gage in 1943. These watersheds were calibrated from 1943 to 1952. Roads were constructed on Fool Creek in 1952 and timber was harvested in 1954 1956. Forty percent of the 714 acre watershed was cut in alternating strips with uncut forest of 1 to 6 tree heights wide (66 to 396 feet). Snow water equivalent was sampled at approximately 100 points on each watershed on or about April 1 from 1943 to 1954 prior to cutting on Fool Creek. Postharvest measurements at the same points were reported for 1959 and from 1967 to 1984. Intensive measurements were made to compare the cut and uncut strips in 1964 and 1979.

The observed peak snow water equivalents on Fool Creek and East St Louis Creek along with the estimated increase on Fool Creek are presented in table 3. This analysis indicates a 1.0 inch (9 percent) watershed wide increase in snowpack water equivalent as a result of the timber harvest on Fool Creek. This is the first reported analysis to indicate an increase in snowpack on the overall watershed. If all of this 1.0 inch increase occurred on the 40 percent cut area, then the average increase on the cut area would be 2.7 inches. This appears well within the 3.4 inches (23 percent) increase reported by Leaf (1975) in comparing the cut and uncut strips on Fool Creek. An additional set of measurements were made on selected strips to check the cut versus uncut snow in 1979. The average increase on the cut strips was 3.8 inches (28 percent).

The exact processes responsible for the increased snow in cut areas are still not clear. Recent work at the Fraser Experimental Forest by Troendle and Meiman (1984) using snowboards in small openings (1.5H) and in the adjacent forests confirmed the increases in the openings, but did not support the concept that snow was redistributed from the forest into the openings during the intervals between storms. Furthermore, the percentage increase indicated by snow-

Table 2.--Net precipitation during spring snowmelt period as a result of cutting (Wilm and Dunford 1948).

Treatment	Inches of water
11,900 f.b.m. uncut	5.73
6,000 f.b.m. residual stand	6.60
4,000 f.b.m. residual stand	7.01
2,000 f.b.m. residual stand	6.94
0 f.b.m. residual stand	7.56

Table 3.--Comparison of snowpack peak water equivalents (inches of water) on Fool Creek and East St Louis Creek Watersheds (Troendle and King 1985).

Year	East St. Louis	Fool Creek	Est. Incr. Fool Creek[1]
1959	12.1	15.8	1.6
1967	9.6	12.2	0.8
1968	11.3	12.7	--0.6
1969	10.0	12.0	0.2
1970	8.0	19.0	0.4
1971	16.3	20.1	1.1
1972	10.6	15.3	2.8
1973	7.8	11.4	2.1
1974	12.7	15.6	0.7
1975	9.8	12.5	0.9
1976	9.2	12.9	0.9
1977	5.8	8.1	1.1
1978	12.8	15.9	0.9
1979	11.4	15.6	2.2
1980	13.9	18.4	2.1
1981	5.4	7.8	1.3
1982	...	...	...
1983	12.6	15.6	0.8
1984	15.1	17.2	--0.5
Average			1.0

[1]Estimated as PWE = PWE (Fool Creek) (0.37 + 1.146PWE East St Louis), R2 = 0.93, standard error = 1.0 inches; where PWE = peak water equivalent.

board measurements were larger than those found by snowpack water equivalent comparisons, thus indicating a relatively greater vapor loss from the snowpack in the openings. The data for the 18 events measured in January through March, 1984 are presented in table 4. The average increase in the opening compared to the windward forest was 31 percent. In only one of the plots was there a significant difference in the downwind plot. Very little redistribution occurred between the 18 snow events. The accumulated amount of snow measured in the openings averaged 133 inches, approximately 0.8 inches or less than 1 percent was measured in the between snowfall intervals.

In order to measure more carefully the water balance effects of patch clearcutting, a plot study was established on a 35 percent north facing slope at the Fraser Experimental Forest at an elevation of 9200 feet. The site was a uniform forest of Engelmann spruce, subalpine fir and lodgepole pine with an average canopy height of 64 feet. In 1980 the site was divided into three equal plots 260 feet wide and 400 feet long. In the summer of 1982 the center plot was clearcut after two years of calibration measurements of snow water equivalent and soil water content. Comparison of peak snow water equivalent for five years are presented in table 5. The increased accumulation averaged 5.8 inches of water or 45 percent more than in the upwind plot (probability < 0.001). Furthermore, there was no significant difference in the downwind forest plot.

Twelve snowboards were placed on each plot and read at 20 different times during the period between January 2, 1985 and April 4, 1985. The boards were read after each storm and during nonstorm periods to determine when storm redistribution occurred. The average accumulation on all boards in the open was 104 inches of snow (depth, not water) compared to 68 inches in the forest giving a 65 percent increase. Virtually all of the increased accumulation occurred during, not after snowfall events. There was no difference between upwind and downwind forest plots. These results confirmed the earlier results (Troendle and Meiman, 1984) obtained on three openings 1.5H in diameter.

The most recently completed study at Fraser of snow accumulation is that of Wheeler (1987). He used the same plots as were used by Troendle and Meiman (1986), but greatly increased the number of events sampled and the sampling intensity. Each snowboard sample was weighed to determine actual water equivalent on the snowboard. In addition to the snowboard measurements, a recording anemometer was installed on a tower at 70 feet above the ground in the center of the clearcut plot. During the period from January to April, 1986, 22 snowfall events and 21 inter storm intervals were observed. Redistribution from the forest to the clearing was observed only one time and accounted for only one percent of the difference in accumulation in the clearing.

Snow accumulation in the upwind and downwind forest was compared for seven storms. None of the storms showed a significant decrease in the mean snow water equivalent in the downwind forest. A comparison of the clearing with the upwind forest indicated a 31 percent greater accumulation in the clearing for the 21 storms. An analysis of average wind speed during the storm as related to the percentage increase in the clearing resulted in a strong negative correlation $r = 0.74$ ($p = 0.002$). The inference drawn from the lack of downwind effect and the negative correlation of snow increase in the opening with increase in windspeed was that snow interception was the dominant process influencing increased snow accumulation in the clearing.

The recommendations from earlier studies that a watershed be treated with 5H circular openings was implemented in the North Fork of Deadhorse Creek in 1977. Timber was removed on 36 percent of the area by commercially clearcutting 12 small units approximately 5H (400 feet) in diameter. All slash was lopped to a 4 inches top and scattered. Comparative snow course observations between Deadhorse and East St Louis Creek began in 1967. Transects consisting of a total of 118 sampling points cross all major slopes, aspects and elevations on Deadhorse. Snow samples using a federal snow sampler are taken about April 1 each year.

Covariance analysis of the pre and post treatment data indicated no overall change in snowpack water equivalent on Deadhorse North Fork Watershed following timber cutting (Troendle and King, 1987). The authors attributed this lack of difference in snow accumulation to the offsetting influence of greater snow ablation in the openings on this south facing watershed. Intensive sampling of several of the openings and the surrounding forest in 1981 indicated an 18 percent greater accumulation in the openings. Because of the potential confounding of differential ablation with accumulation processes,

Table 4.--Comparison of snow accumulation (inches) in the forest and open averaged for 18 snow events and comparison of peak snowpack water equivalent (percent) on April 1.

Unit	Windward forest	Open	Leeward forest	% Increase in open	% Increase in snow water in open, April 1.[1]
1	5.7	7.4*	4.8*	30.3	26
2	4.5	5.9*	4.1	31.6	16
3	4.5	5.9*	4.3	31.6	16

*Significantly different from windward forest at P = 0.05.

[1]Federal snow sampler measurements.

Table 5.--Peak snow water equivalent (inches) as a result of timber cutting (Troendle and Meiman 1986).

Year	Upwind plot	Cut plot	Downwind plot
1981	6.1	6.2	6.1
1982	12.2	12.5	12.5
		-------- Center plot cut --------	
1983	11.9	17.2*	12.3
1984	14.8	21.3*	14.4
1985	11.8	17.5*	Missing

*Significantly different from upwind plot ($p < 0.001$).

it is not possible to separate interception and differential deposition processes in this data.

One final study deserves mention in relation to clearcutting. The optimum size of clearcuts generally has been given as approximately 5H (Troendle, 1983) with the assumption that larger openings are subject to wind scour. A study was initiated in 1981 to see if larger openings would hold more snow than the adjacent forest if sufficient roughness were maintained in the form of slash and non commercial trees (Troendle and Meiman, 1984).

In 1981 an 20 acre area surrounding one of the original 8 acre clearcut plots studied by Wilm and Dunford was clearcut along with the original 8 acre area. All merchantable trees were removed, the slash lopped and scattered and most of the larger trees felled. About 4 to 6 cavity trees per acre as well as the non commercial stems less than 6 inches d.b.h. were left standing.

In the summer of 1983, all remaining trees on the site were felled. A layer of slash up to 24 inches high remains. Peak snowpack water equivalent measured around April 1 in 1982 and 1983 after the original 8 acre plot (5 acre cut + 3 acre boundary) was recut produced no scour in the original 8 acre area as a result of the now 28 acre opening. This indicated there was still enough roughness in the slash and remaining trees to protect the area from scour. After the removal of all remaining trees in 1983, the accumulation patterns were as presented in figure 1. These results suggest that the slash is still an effective snow trap in the large opening, but once the snowpack reaches the level of the slash then effectiveness decreases.

Thinning Studies

Beginning with the work of Wilm and Dunford a number of studies have been conducted at Fraser over the years on the effects of partial cutting on snow accumulation. These studies have been somewhat overshadowed by the Fool Creek cutting and the emphasis on small clearcuts as the preferred water yield management practice.

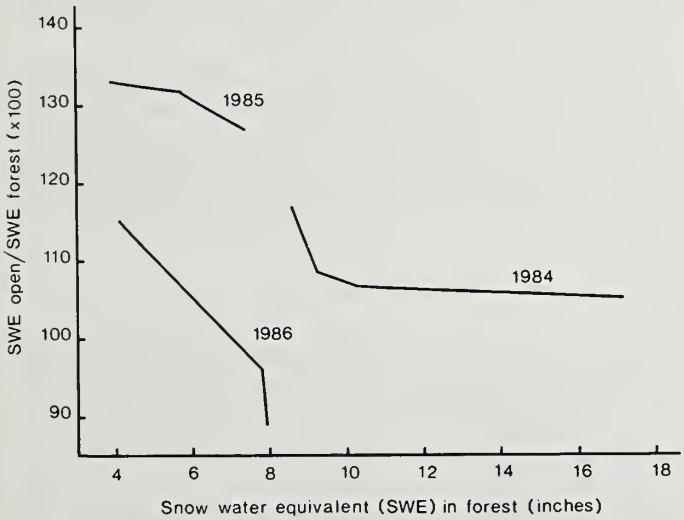

Figure 1.--Comparison of snow water equivalent in open to forest as season progresses.

Hoover and Leaf (1966) presented data on follow up measurements on the original Wilm and Dunford plots. Their measurements for 1956 and 1964 have been added to the original data and are presented together as table 6. In presenting the remeasured plot data, Hoover and Leaf emphasized that the relative snow storage amounts had changed little if any between 1941 and 1964 in spite of the considerable regrowth of young trees and increased canopy density on the more heavily cut plots. They attributed the effect on the 0 and 2,000 f.b.m. plots to the trapping of snow from surrounding old growth trees, but pointed out that a longer regrowth period was needed for more conclusive results. It is of interest to note that the 6,000 and 4,000 f.b.m. thinning effects persist as well as those on the more heavily cut plots.

Troendle and Meiman (1984) analyzed records for one of the original Wilm and Dunford clearcut plots for the period 1941 through 1981. This analysis indicated that the increased snow accumulation in the clearcut area has been diminishing by 0.028 inches per year since 1941. In the 40 year period the recovery was 1.14 inches of the original 2.95 inches difference. Using a linear fit, total recovery would take 103 years. However if the nonlinear growth curve is assumed, total recovery could be expected in a shorter period of time.

Peak snow water equivalent has been measured on four different stand densities in lodgepole pine beginning in 1978. Each thinning level is applied to a 0.5 acre site and replicated five times. These data are presented in table 7 and have been reported in part in Gary and Troendle (1982) and Troendle

Table 6.--Snow storage on lodgepole pine harvest plots.

Merchantable reserve stand per acre (f.b.m.)	Before treatment 1938-9[1]	1941-3[1]	After treatment 1956[2]	1964[2]
	---------- (Inches of water) ----------			
11,900, uncut	6.5	7.0	8.4	4.8
6,000	6.8	8.0	----	5.6
4,000	6.9	8.7	10.8	6.3
2,000	7.0	9.7	----	6.8
0	6.8	9.7	11.6	6.7

[1]From Wilm and Dunford 1948, unadjusted data.

[2]From Hoover and Leaf 1966.

Table 7.--Maximum snowpack water equivalent (inches) as related to basal area (ft^2 per acre).

Year	---------- Basal 140	area 120	---------- 80	40
1978	9.9	9.1	9.6	10.2
1979	8.7	8.9	9.8	10.4
1980	10.5	11.2	11.6	12.1
1981	--	3.3	3.5	3.9
1982	8.3	8.3	8.9	8.9
1983	9.1	9.5	9.5	10.1
1987	6.0	5.8	6.4	6.4

and Meiman (1984). There is a consistent significant difference ($p = 0.05$) between the 40 and 140 levels. Although there is a general trend of increased snow water equivalent with decreased basal area at the intermediate levels, these are not statistically significant.

A much larger scale thinning study was established on Unit 8 of Deadhorse Creek. Unit 8 is a 100 acre north facing slope that was partially cut in 1980 in the first step of a three step shelterwood cut. Approximately 40 percent of the basal area was removed as individually marked trees 7 inches d.b.h. and larger. Peak snowpack water equivalent on Unit 8 was compared to that on the East St Louis Creek control for 14 years prior to thinning and four years after. The r value for the pretreatment correlation was 0.98 with a standard error of 0.2 inches. Peak water equivalent compared to the control increased 1.9 inches or 16 percent over the entire unit (Troendle and King, 1987). The results from this study indicate that the thinning effects found on plot studies also apply to larger thinned areas and, therefore, strongly suggest that the process responsible is interception.

Troendle (1987) in attempting to summarize data on thinning and clear cutting at Fraser and related studies developed the relationship presented in figure 2 illustrating the general relationship between basal area and snow accumulation.

Summary and Management Implications

Fifty years of studies at Fraser have given us a wealth of information on the influence of forests on snow accumulation. There is ample evidence that both clearcutting and thinning produce significant increases in snow accumulation on the treated areas. The increase on Fool Creek in the cut areas appears to be approximately 23 percent and on the North Fork of Deadhorse Creek approximately 18 percent. Considering the entire watershed including cut and uncut areas, there is an overall 9 percent increase on Fool Creek and no increase on North Fork of Deadhorse Creek. These effects of clearcutting small areas appear to be long lived, at least well beyond the almost 50 years of records to date. There is also some evidence that we can achieve snow accumulation increases on cut areas larger than 5H if we pay attention to maintaining sufficient surface roughness through slash disposal and residual trees.

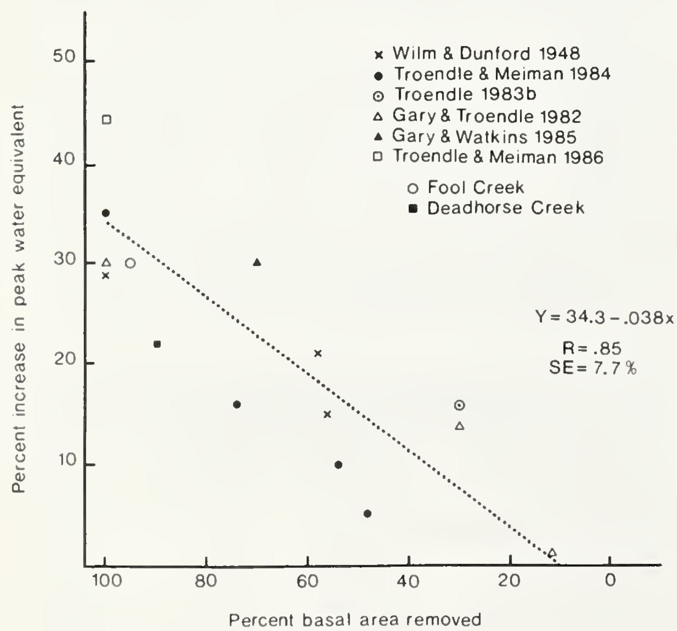

Figure 2.--Summary of cutting experiments at Fraser (Troendle 1987).

Increases from thinning are somewhat more variable, but information to date indicates increases from 10 to 25 percent for basal area reductions of from 40 to 80 percent respectively.

Demands on forest managers can change over time therefore the best knowledge base for sound management is a thorough understanding of processes responsible for changes brought about by different management practices. The effects from both thinning and clearcutting have been demonstrated on watershed as well as on plot studies. However a thorough understanding of the processes responsible is not yet in hand. The longer data base now available indicates a 9 percent net increase of snow on the overall watershed on Fool Creek thus suggesting interception savings are important. We have not found significant redistribution of snow from forest to openings during the intervals between storms. Still inseparable are the processes of interception and differential deposition during snowfall events. Hopefully the snowfall process studies using snow particle counters now underway at Fraser will help us define better what is happening during snowfall events. We have not found consistent decreases of snow accumulation in forests downwind from openings. In those instances where such decreases have been observed, it is not clear to what extent wind scour has moved snow deeper into the forest. There is also evidence that differential ablation in the open areas and adjacent forest borders is a more important factor in the subalpine than previously thought.

All of the above reinforce the need to continue the process studies together with the larger area watershed measurements. It is this combination of integrated process, plot and watershed studies that has made Fraser such a valuable source of information for land managers through these past 50 years.

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Influence of Forests on the Hydrology of the Subalpine Forest

C. A. Troendle and M. R. Kaufmann[1]

Abstract--Forest vegetation is important in the hydrology of subalpine ecosystems. First, leaf surface area of the canopy presents a massive intercepting surface to both rain and snowfall, much of which subsequently is evaporated back to the atmosphere. The same canopy biomass also transpires significant amounts of water, thereby depleting soil water reserves and increasing storage capacity for subsequent rain or snowmelt that reaches the soil. Reducing the canopy biomass by either partial or clearcutting decreases the interception loss, decreases overstory transpiration, increases understory water use, decreases soil water depletion, and may increase total streamflow, peak flow, and base flow. Increasing stand density has the reverse effect. This paper describes the processes influenced as the forest vegetation is manipulated.

The original classic water balance study in the United States was done at Wagon Wheel Gap on the headwaters of the Rio Grande in southwestern Colorado (Bates and Henry 1928). Streamflow from two watersheds was monitored from 1911 to 1919, and then one watershed was clearcut. In addition to daily streamflow, other factors, such as temperature, humidity, evaporation, and soil moisture, also were monitored. The authors noted that, of the 21 inches of annual precipitation falling on the watershed, approximately 6 inches was returned as streamflow, with almost 15 inches lost to winter and summer evapotranspiration. Following harvest, evapotranspiration was reduced and flow increased an average of about 1 inch. Based on site-specific estimates, the authors partitioned the vapor losses into snow interception, winter and summer ground evaporation, and transpiration. They concluded that (1) much of the opportunity for the observed increases in flow came from net reduction in winter losses, and (2) much of the reduction in overstory transpiration was offset by increased understory transpiration and ground evaporation.

The objective of this paper is to define the water balance of the subalpine forest as we understand it today, as it is reflected in streamflow. The process that we are defining begins with the input of precipitation, considers the opportunities for vaporization, addresses the streamflow generating or transport processes, and identifies the excess or streamflow. In a separate effort, Meiman (1987) addressed the influence of forest on winter snowpack accumulation, and defined the opportunities for influencing that portion of the water balance. In this paper, it will be necessary to use some of the numbers he presented to arrive at annual water balances and estimates of streamflow.

The format for this presentation will be to (1) describe hydrologic response and streamflow generation in the subalpine; (2) describe the annual water balance as indexed by the difference between gross precipitation and measured streamflow, and the integrated changes in that balance that the presence or absence of forest cause at the streamgage; (3) describe the process studies attempting to define the components of the water balance and the role forests play on those processes; and (4) look at the role forests play in mitigating watershed response, with respect to snowmelt peak and individual storm response.

Hydrologic Background

The precipitation regime entering Fraser Experimental Forest is typical of central Rocky Mountain subalpine watersheds. At Fraser, approximately 25 inches of precipitation falls in the headquarters area at 9,000 feet elevation, uniformly distributed through the year. The range is from 15 to over 30 inches, with approximately two-thirds occurring as snowfall. The watersheds yield 45% to 55% of that precipitation as streamflow. About 70% of this water yield comes in April, May, and June as the direct result of snowmelt, 5% or less comes directly from summer rainfall, and 25% from a stable and perennial baseflow. Most of the baseflow is indirectly generated from snow. Garstka (1958) estimated 90% to 95% of the total annual yield of the Fraser streamflow comes from snow.

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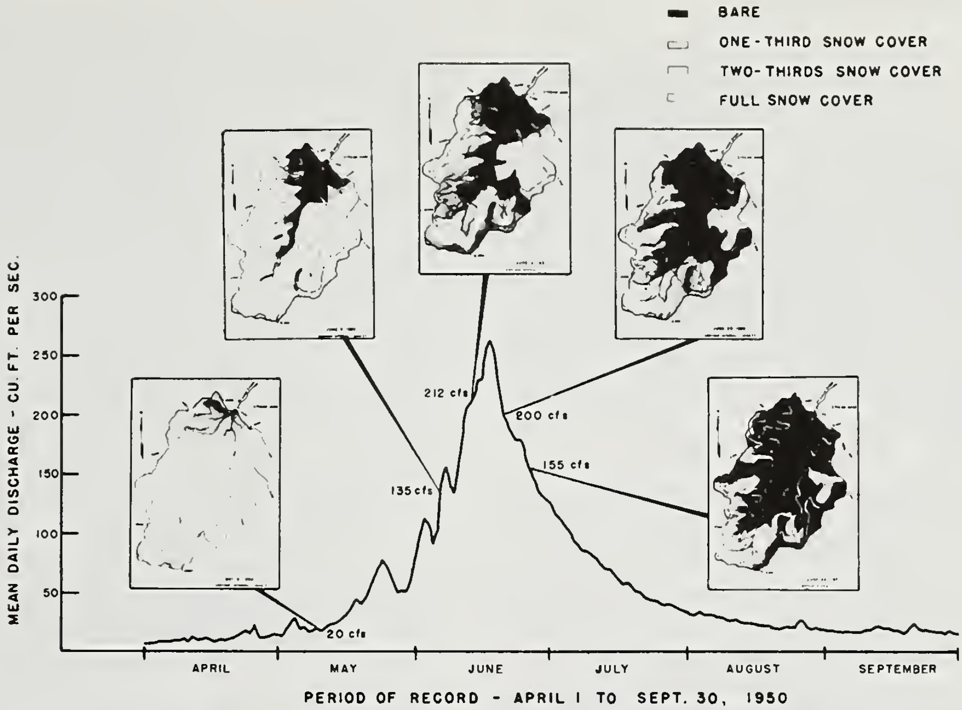

Figure 1.--Snow cover in relation to streamflow (from Garstka et al. 1958).

Figure 1 depicts the relationship between snow cover and the annual hydrograph of the St. Louis Creek watershed at Fraser. It should be noted, however, that the amount of precipitation, the timing of melt, and the generation of runoff are all a function of aspect, elevation, soils, geology, and vegetal cover. Figure 1 represents an integration of everything that is occurring above the streamgage, as does any measured flow data, and there is significant variation within the system.

Fool Creek, on the Fraser Experimental Forest, is a 714-acre watershed, ranging in elevation from 9,500 to 11,500 feet. Currently, two streamgages monitor flow, one from the entire drainage and one at an elevation of 10,500 feet (fig. 2). The upper flume gages the uppermost 162 acres of the drainage consisting of noncommercial forest and krummholtz. Figure 3 presents hydrographs from the entire drainage, that part contributed from the "alpine" area, and that part from the lower forest or harvested area. Flow from the entire drainage was 14.6 inches in 1986: 22.1 inches from the 162-acre alpine area, and 12.4 inches from the 552-acre lower forested portion. The differences in total flow reflect both precipitation and evapotranspiration differences. Most evident, however, is the desynchronization in flow between the lower (9,500 to 10,500 feet) and upper (10,500 to 11,500 feet) portions of the watershed. Both portions contributed more or less equally to peak discharge rate, but the flow volume around the peak was controlled by the larger lower portion (552 acres). A secondary peak, from the alpine area, came 10 days later, and influenced the total watershed flow.

It appears as though both portions contribute equally to baseflow. However, a large storm (1.8 inches of accumulated precipitation) in late July caused a response on the lower portion of the watershed containing the majority of seep areas and live channel, but not from the upper drainage. Storm response for the watershed was only 3% or 4% of the precipitation. For the most part, the upper watershed-lower watershed comparison demonstrates the temporally differential contribution from the high and low elevations that occur on subalpine watersheds.

Since we do not have adequate precipitation data from the alpine area, we cannot estimate the water balance for that drainage. However, flow from the lower portion is less than the average for the entire watershed; therefore, we have been underestimating ET (as P - RO) on that forested portion. The lower, fully forested (although harvested) portion of Fool Creek appears to have a water balance more similar to that for the North Fork of Deadhorse Creek, another unit with no noncommercial alpine area. Figure 4 depicts the unit area contribution from both portions of the watershed, and the alpine area is the far greater contributor.

Effect of Timber Harvest on Water Yield

Numerous paired watershed experiments have been conducted to determine the effect of forest manipulation on the water balance and water yield. Regional summaries have been presented by Douglass (1983), Harr (1983), Hibbert (1983), Kattelmann et al. (1983), and Troendle (1983), while Bosch and Hewlett (1982) summarized the almost 100 experiments world wide. For this paper, we are primarily concerned with those experiments conducted in the subalpine environment.

Fool Creek

Although the Wagon Wheel Gap experiment (mentioned earlier) was the first of its kind in the United States, the Fool Creek watershed study at Fraser is considered the classic because of its long-term record. Streamflow from the 714-acre Fool Creek and its 1,984-acre control, East St. Louis Creek, was gaged for 11 years prior to harvest in 1954-56. Forty percent of the watershed (50% of merchantable forest) was clearcut in alternating cut and leave strips that varied from 1 to 6 tree heights (H) in width and 500 to 600 feet long. Snow courses also were located on each watershed and monitored from 1943 to 1954, in 1956, and from 1966 to present. Troendle

Figure 2.--Fool Creek watershed showing location of streamflow-generating springs and seeps, as well as the location of the two streamgages.

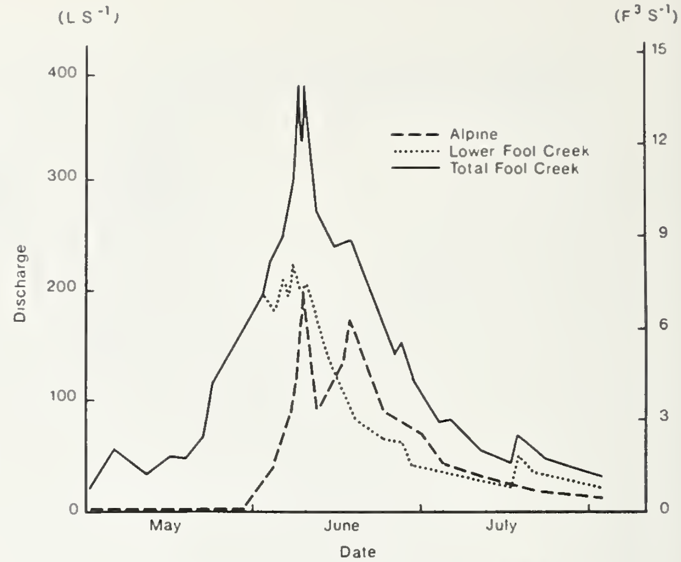

Figure 3.--Daily discharge from the Fool Creek watershed and the contribution made by each component.

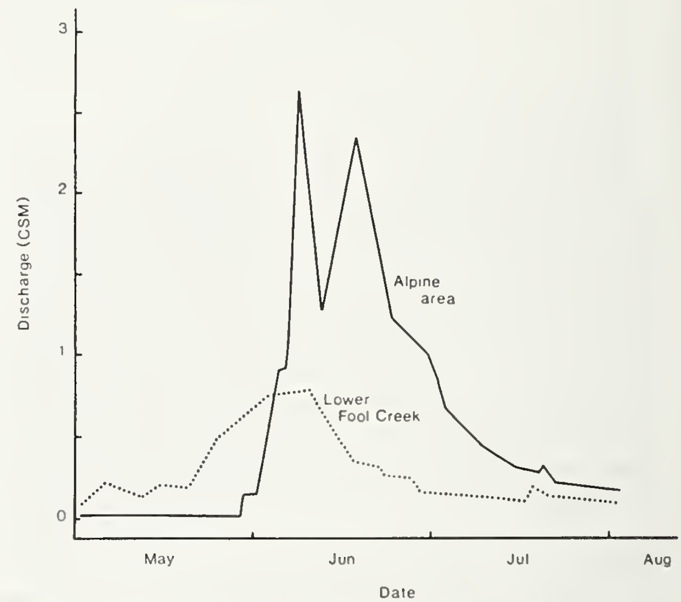

Figure 4.--Unit area discharge from the 162-acre alpine area and the 552-acre lower portion of Fool Creek.

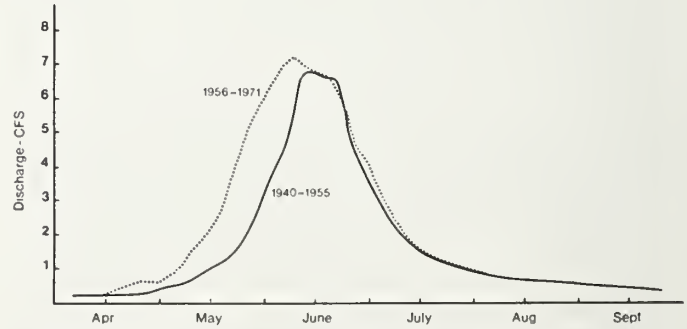

Figure 5.--Average hydrographs from Fool Creek for before (1940-1955) and after (1956-1971) harvest.

and King (1985) recently summarized the effects of that treatment. Flow increased an average of 3.2 inches for the first 28 years after treatment. The first year average increase (increase that would be expected to occur under average climatic conditions) was 4 inches, actual increases were precipitation dependent, and the largest increases (up to 6.4 inches) occurred in the wettest years (table 1).

Two significant observations were made in the recent analysis. First, peak snowpack water equivalent actually increased over the entire watershed by 9%, presumably as a result of reduced interception. Second, for the first time, precipitation records were adequate to allow interrogation of the relationship between various precipitation parameters and flow or change in flow (Troendle and King 1985). The fitted equation was

$$\Delta Q = 0.27 + 0.067\ PWE + 0.11\ SPRPC - 0.04\ t$$

where

ΔQ = estimated increase in flow (inches),
PWE = peak water equivalent on April 1 (inches),
SPRPC = melt period (April 1--July 1) precipitation,
t = time in years since harvest,
Adjusted R^2 = 0.62, and
Standard Error = 0.72 inches.

Table 1.--April to September streamflow from East St. Louis Creek and Fool Creek, and an estimate of the increase (in inches) from Fool Creek due to timber harvest (Troendle and King 1985).

Year	Observed runoff East St. Louis Creek	Observed runoff Fool Creek	Estimated increase Fool Creek[1]
1956	15.6	13.9	3.7
1957	21.4	20.8	6.4
1958	13.1	12.0	3.5
1959	11.9	11.9	4.3
1960	13.9	13.7	4.7
1961	10.1	9.6	3.3
1962	18.7	17.3	4.8
1963	5.2	4.3	1.6
1964	10.1	9.0	2.7
1965	17.5	15.6	3.9
1966	7.8	6.8	2.2
1967	12.6	11.0	3.0
1968	11.7	9.1	1.6
1969	14.6	12.1	2.6
1970	18.4	14.8	2.5
1971	17.8	15.8	3.9
1972	12.3	11.7	3.8
1973	15.2	12.2	2.2
1974	16.0	13.8	3.3
1975	12.7	10.4	2.2
1976	9.5	7.7	1.8
1977	8.0	6.2	1.4
1978	14.6	12.9	3.4
1979	12.8	10.6	4.0
1980	13.4	11.7	3.0
1981	8.3	6.7	1.7
1982	15.2	15.4	5.4
1983	22.6	20.3	5.0

[1]Estimated as $\Delta Q = Q_{F.C.} + 0.94 - 0.717Q_{E.S.L.C.}$ $R^2 = 0.84$, standard error = 1.1 inches; where ΔQ is the increase in flow on Fool Creek (inches); $Q_{F.C.}$ is the runoff on Fool Creek (inches); and $Q_{E.S.L.C.}$ is the runoff in East St. Louis Creek (inches).

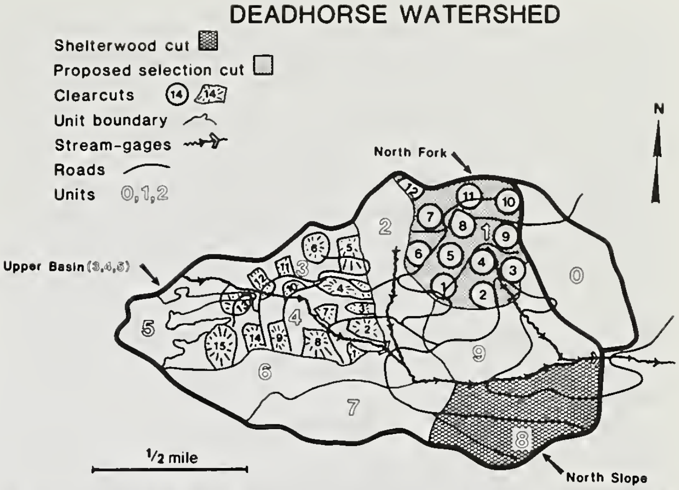

Figure 6.--The Deadhorse complex showing harvesting alternatives applied to the North Fork, North Slope, and Upper Basin.

Summer precipitation (July 1 through October 15) did not significantly correlate with change in flow. It is difficult to interpret the causal relationships between flow, change in flow, and the precipitation parameters in the subalpine environment. Summer precipitation appears to be lost, regardless of presence or absence of vegetation, yet increases in flow are totally precipitation dependent. We obviously are dealing with an arid environment where evaporative losses are significant and influenced by vegetation year round. The average hydrographs for before and after harvest are shown in figure 5. Most of the flow increases came in May. Other monthly flows were virtually unaffected.

Increased flow on Fool Creek has been decreasing at a rate of 0.04 inch per year. The increased peak water equivalent also appears to be decreasing. As the vegetation regrows, the summer and winter ET losses increase, thereby diminishing the increased flow. Analysis of streamflow records indicates the effect of treatment will last 80 years. Separate simulations of stand growth using Rocky Mountain Yield indicate the original leaf area will regrow in 70 to 80 years.

Deadhorse Creek

More recently, the Deadhorse watershed complex was installed and treated. Main Deadhorse Creek (fig. 6), a 640-acre watershed on the Fraser Experimental Forest, was first gaged in 1955. In 1970 and 1975, streamgages also were built on the North Fork and Upper Basin subdrainages. The main watershed and two subdrainages are calibrated against East St. Louis Creek, the 1,984-acre control watershed.

The first treatment was imposed on the North Fork subdrainage in 1977 (fig. 6), when 12 small units were commercially clearcut (Troendle and King 1987). The circular openings were 5-H in diameter and occupied about 3 acres each. Approximately 12,000 b.f.a. was removed per acre clearcut, and 36% of the watershed area was harvested (Troendle 1983a).

In 1980 and 1981, unit 8 (fig. 5) was harvested in the first step of a three-step shelterwood cut. Unit 8 is an ungaged, north-facing slope, 100 acres in area, that lies downstream of both the North Fork and Upper Basin subdrainages and is a part of the 348-acre interbasin area above the main streamgage. Approximately 40% of the basal area was removed by individually marked trees 7 inches d.b.h. and larger. The entire 100 acres was harvested uniformly, removing a total of 730 m.b.f. of sawtimber or 7.3 m.b.f.a. Although the percentage of the total stand removed was the same on the North Fork (36%) and North Slope unit 8 (40%), a greater volume of sawlogs was removed from the North Slope (Troendle and King 1987).

During the summers of 1983 and 1984, approximately 30% of the gaged Upper Basin was harvested in irregularly shaped clearcuts, varying in size from 2.5 to 15 acres. The impact of harvest on the hydrology of the upper basin cannot be addressed yet.

The 5-H circular clearcuts imposed on the North Fork were intended to maximize snowpack accumulation in the clearcuts, and to optimize flow increases for the basal area removed. In contrast, it was reasoned that partial cutting would have little effect on streamflow because (1) in a semiarid environment such as the subalpine (Leaf 1975), the residual stand would have access to and use any transpirational savings during the growing season; and (2) without clearcutting and the attendant aerodynamic changes, there would be no redistribution of snow, no net change in the deposition pattern of the winter snowpack, and, therefore, the presumed efficiency in delivering water to the stream because of snow redistribution would not be attained. The hypothesis in this assumption was that partial cutting (harvesting by individual tree removal or thinning) would be far less efficient in increasing streamflow than would be the removal of the same percentage of the forest in small (5- to 8-H) clearcuts.

Table 2 lists the flow increases from the North Fork since 1978. The average increase has been 2.4 inches; the variation from 0.8 to 4.2 inches can be attributed to annual differences in precipitation. As was done for the Fool Creek watershed, the individual increases in flow (Q) were regressed on (1) winter precipitation (October 15 through March 30), (2) spring or melt period precipitation (April 1 through June 30), and (3) growing season precipitation (July 1 through October 14). Because of the short posttreatment record, a time or recovery variable (t) was not included in the regression. Winter precipitation (peak water equivalent) entered the equation first ($r = 0.74$, $p = 0.03$), spring precipitation second ($p = 0.06$), and growing season precipitation third ($p = 0.11$). The adjusted R^2 for the multiple fit was 0.76; little was contributed once winter and spring precipitation were considered. As a check, total flow from the North Fork was regressed on the same variables, and the same relationship existed for both the pre- and postharvest periods, indicating that timber harvest did not alter the relative significance of the driving precipitation variables. Summer precipitation was relatively nonsignificant before harvest and remained that way after harvest.

Table 2.--Observed flow and estimate of increase due to timber harvest on the North Fork of Deadhorse Creek (Troendle and King 1987).

Year	Observed flow (Inches)	Increase in flow[1] (Inches)
1978	10.6	3.2
1979	8.3	4.2
1980	9.1	2.6
1981	3.7	1.4
1982	11.2	3.3
1983	14.6	0.8
1984	15.6	1.2
$\bar{x}$	10.4	2.4

[1]Increase is estimated as: $\Delta Q = QDH - (0.81\ QESL - 4.41)$, where: ΔQ = change in flow, North Fork (inches); QDH = observed annual flow, North Fork (inches); QESL = observed annual flow, St. Louis Creek; $r^2 = 0.98$; and std. error of est. = 0.43.

In a somewhat similar analysis, Troendle (1983) found that the annual variability in total flow and the increases in flow from Wagon Wheel Gap also were highly correlated with precipitation. Low years yielded small increases.

The calibration of flow from the interbasin area on Deadhorse Creek, which includes unit 8, on flow from the control, East St. Louis Creek, was good ($r = 0.9$, standard error = 0.6 inch). Covariance analyses of the adjusted group means for the 6 pretreatment and 3 posttreatment years indicated that flow from the entire 348-acre interbasin area may have increased 1 inch ($p = 0.34$) after partial cutting. This represents a unit area increase of about 3.6 inches from the 100-acre area actually harvested. However, the posttreatment years so far have had well above average precipitation, and we expect the observed increases to be lower under drier or average conditions. The hypothesis in establishing the treatment, however, was that partial cutting would have no effect on water yield.

The calibration of main Deadhorse Creek on its East St. Louis Creek control has an R^2 of 0.95 and a standard error of 0.3 inch based on a 21-year calibration. After 4 years of postharvest record on the North Fork, Troendle (1983a) noted that the significant increase in flow detected at the North Fork gage could not be detected downstream at the main gage. Covariance analysis at that time indicated that mean flow from the 640-acre Deadhorse Creek increased an average of 0.7 inch for the period 1978-1981, but it was not significant ($p = 0.37$).

Currently, covariance analysis still indicates the 1978-1983 adjusted mean for the watershed has not increased significantly, although the net effect of both treatments may have increased the flow 0.6 inch ($p = 0.31$). As stated, estimated change in flow at the main streamgage of 0.6 inch is not significant (at $p = 0.05$), but it is very reasonable, considering the measured change on the North Fork represents a mean change of 0.33 inch over the entire Deadhorse watershed, and the partial cut on the North Slope contributed an estimated 0.35 inch. The total (0.33 + 0.35) of 0.68 inch compares well with the measured estimate of 0.6 inch at the main gage.

Sturgis Watershed 3

The effect of partial cutting was more definitively evaluated in the ponderosa pine type in the Black Hills, near Rapid City, S. Dak., at the Sturgis experimental watersheds (Anderson 1980).

Sturgis watershed 3 is a 190-acre experimental watershed that flows to the north from an elevation of 5,700 feet. It has a total relief of 700 feet. The basic hydrology, geology, and geomorphology of watershed 3 and its 90-acre control, watershed 2, were described by Orr (1969) and Yamamoto and Orr (1972).

After a 7-year calibration period, logging began on watershed 3 in late summer 1970 and finished in 1971. The intent was to reduce the basal area on 130 of the 190 acres to a growing stock level (GSL) of 70. Postharvest surveys showed that, although only about one-half of the watershed area was harvested, approximately 25% of the total basal area on the entire watershed was removed.

The average annual increase in flow was 1.9 inches ($p < 0.001$) for the years 1972-79, with a yearly range from 0.6 to 3.8 inches. Forty-two percent of the increase occurred in April, 19% in May, and 25% in June, for a total of 86% in the 3-month runoff period.

As for the Fraser watersheds, annual precipitation for watershed 3 was divided into three seasonal values--winter (November-March), spring (April- June), and summer (July-October)--and this precipitation parameter was correlated with the observed changes in flow (Troendle 1987). During the 7 postharvest years, winter precipitation averaged 7.2 inches, with a standard error of 2.6 inches, spring precipitation averaged 13.7 ± 6.1 inches, and summer precipitation average 8.1 ± 2.4 inches. The mean precipitation for the watershed averaged 29.0 ± 4.6 inches per year.

Both in terms of total annual streamflow and change in flow after harvesting, spring precipitation was the parameter most significantly correlated with response ($p = 0.01$, $r = 0.50$). Winter precipitation, although significant, was only slightly correlated ($r = 0.10$) with both flow parameters. Summer precipitation was negatively correlated with both flow and the increase in flow ($r = -0.42$ and -0.50, respectively). However, because summer precipitation was negatively correlated equally with total annual and with spring precipitation, the postharvest summer precipitation (either expressed as current precipitation or lagged 1 year to represent previous or antecedent precipitation) was not correlated with either total flow or the change in flow.

Effect of Timber Harvest on Peak Discharge and Storm Response

Peak Discharges

Most watershed experiments in the subalpine environment have demonstrated an increase in peak discharge following vegetation removal. Van Haveren (1981), reanalyzing the data from Wagon Wheel Gap, found that peak discharge increased 50% following clearcutting, although the date of peak flow did not change.

On Fool Creek, Troendle and King (1985) found that, during 28 years of postharvest record, peaks increased an average of 23% and that the increased peaks were positively correlated with peak water equivalent in the snowpack. Unlike Wagon Wheel Gap, the timing of the peak was altered on Fool Creek; the faster melt and quicker satisfaction of soil moisture recharge requirements caused the flow to peak an average of 7.5 days earlier. A second significant observation is that the increase in peak flow, like the increase in total flow, is beginning to diminish with time ($p = 0.10$).

Peak discharge from the North Fork of Deadhorse Creek increased about 50% ($P = 0.07$). However, like Wagon Wheel Gap and unlike Fool Creek, the timing of peak did not change following harvest (Troendle and King 1987).

Peak discharge at the main Deadhorse gage would reflect any impact due to the partial cut on the North Slope and the North Fork clearcuts. No change was detected in either the magnitude or the date of occurrence of the peak discharge at the main Deadhorse gage.

In summary, it appears that timber harvest increases peaks on site, but may or may not influence timing. Even when timing is influenced, it is only shifted 1 week. The downstream effect of peak flow increases probably is minimal.

Stormflow

In a plot study on a 35% west-facing slope above a lateral moraine, Troendle (1985, 1987b) monitored the lateral migration of melt water from the snowpack to the soil, and toward the stream channel. In 1978 and 1979, two subsurface flow collection systems were installed on two separate portions of the 25-acre study area. The collection system on plot 1, a slightly divergent slope, was 50 feet wide, while it was 120 feet wide on plot 2, a slightly converging slope. Both slopes were 700 feet long, and both collection systems were 13 feet deep. They intercepted water moving laterally downslope from the surface, the shallow subsurface (upper 3.3 feet of soil), and from the deep subsurface (from 3.3 to 13 feet). In addition to outflow by horizon, the elevation of perched water tables was also continuously monitored, as were winter snowpack accumulation and precipitation.

Figure 7 depicts typical outflow for the two plots prior to harvest. The scenario is that as snow melts, it infiltrates and percolates, primarily vertically, until an impedance slows it down. The saturated conductivity goes from in excess of 8 inches per hour at the 1-foot depth to 0.001 inch per hour at the 7-foot depth. Since snow can melt at rates up to 0.8 inch per day, the permeability rate can become limiting at depths of 5 to 6 feet at this site; a perched water table develops and rises toward the surface as melt continues. With the creation of the perched water table, lateral migration becomes significant and plot outflow, spring flow, or streamflow is generated. Except

for a small portion of surface flow on plot 2, virtually all flow is subsurface (fig. 7). In addition, in excess of 90% of all flow is deep subsurface in nature. Outflow varied with amount of precipitation and usually ended by July or August, with the growing season precipitation retained or used on site.

In late 1984, plot 1 was clearcut to follow the effect of clearcutting on snowpack accumulation, melt, and lateral translation. Figure 8 represents comparative hydrographs from the cut and uncut plots. Following the first full year after harvest, the soils were wetter on the cut plot, as was demonstrated earlier. This required less soil water recharge. Secondly, snowmelt may have occurred earlier and faster, causing flow to begin on the cut plot 1 month earlier than on the forested plot. Peak flow rate was appreciably increased, as was total volume of flow. However, the snowmelt recession side of the hydrograph appeared unchanged, and both plots quit flowing at the same time. Soil moisture content on the forested plot continued to be depleted by evapotranspiration much faster than on the clearcut plot. As a result of several storms, flow initiated a second and then a third time on the clearcut plot. Although at a low rate, the outflow represents a significant increase due to harvest.

This case study provides much insight into processes that generate streamflow, and the effect of management on those processes. And for the first time, it identifies the fact that we may be increasing baseflow from harvested areas.

Effect of Timber Harvest on Water Balance

As noted earlier, Bates and Henry (1928) presented one of the first attempts to quantify components of the water balance based on data from Wagon Wheel Gap. Wilm and Dunford (1948) presented a most thorough water balance study in the lodgepole pine type at Fraser. Five harvest plots representing a control, a clearcut, and three levels of partial cutting (0, 2,000, 4,000, 6,000, 12,000 b.f.a. reserve volume) were replicated in

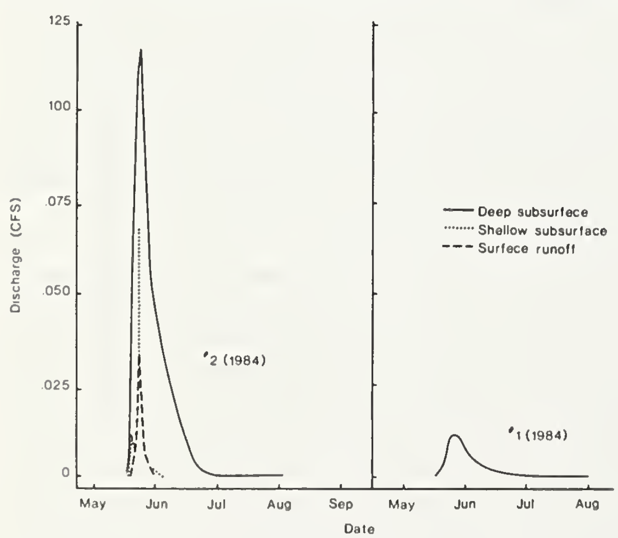

Figure 7.--Outflow hydrographs for plots 1 and 2 for 1984.

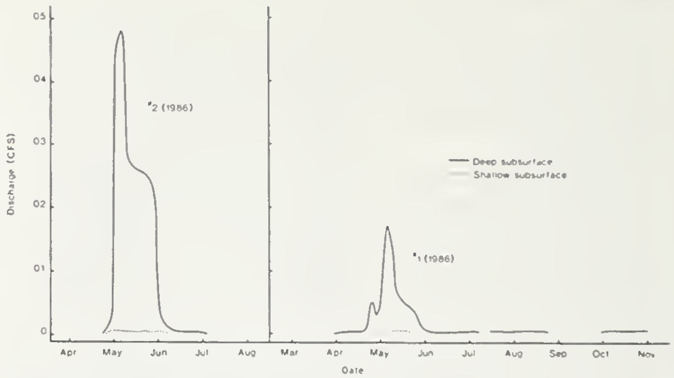

Figure 8.--Outflow hydrographs for plots 1 and 2 for 1986. Plot 1 was clearcut in late 1984.

each of four randomized blocks. They monitored snowpack accumulation, gross precipitation, throughfall precipitation, stemflow, soil moisture (to 18 inches), and evaporative loss. They also estimated evapotranspiration and interception loss.

First, they noted that peak water equivalent in the snowpack increased linearly with reduced stand volume (table 3). Secondly, they noted that overstory interception losses and soil water depletion rates were reduced with reduced stand density. Table 3 notes the changes in the evaporative components they monitored. They concluded that water available for streamflow increased (net ET reduction, table 3) because of both winter and spring interception savings, as well as summer ET reductions. Observed changes in soil water depletion (reflecting a transpiration reduction) were minimal, but they only monitored the upper 18 inches of soil. Subsequent studies indicate significant depletion can occur to 3 feet or more in depth (Troendle 1987a).

In a second water balance study at Fraser, Troendle and Meiman (1986) worked with a north-facing slope. In an unreplicated case study, they divided a 7-acre area, on a uniform 35% north-facing slope, into three contiguous blocks that joined each other on an east-west axis. The stand was a uniform forest of Engelmann spruce, subalpine fir, and lodgepole pine, with an average height of 69 feet.

Ten-neutron probe soil moisture access tubes and 15 snow stake sampling points were systematically located in each block. After 2 years of calibration, the center block was clearcut. Figure 9 depicts the accumulation and ablation pattern on that site, and although significantly more water is stored in the open, it ablates during the same time period, implying a higher melt rate in the open. This process contributes to the greater runoff peaks observed at the watershed level.

Generally, all three blocks were at the same soil moisture recharge level in early June. Soil moisture content on each block then was remeasured two or three times per growing season for 3 years following harvest. Depletion (or recharge) is estimated by looking at differences in moisture content between successive measurements. Evapotranspiration for the measurement interval is estimated as the summation of the change in soil moisture content for the interval plus the

Table 3.--Summary of the effect of different harvesting levels on the water balance of lodgepole pine (Wilm and Dunford 1948).

Lodgepole pine reserve volume	Increase, peak water equivalent[1]	Increase, spring precipitation[2]	Summer interception reduction[3]	Reduced soil water depletion	Net ET reduction[4]
- - b.f.a - -			inches		
12,700 (uncut)	0	0	0	0	0
6,000	0.8	0.3	0.6	0	1.1
4,000	1.0	0.5	0.8	0.5	2.0
2,000	1.5	0.2	0.9	0.4	2.1
0 (clearcut)	2.0	0.5	1.2	0.6	3.2

[1]Net change in winter snowpack on April 1.

[2]Estimate of net increase in gross precipitation to the ground during melt period.

[3]Measure of interception savings lost to ET. Not included in ET savings.

[4]Sum of components; represents increase in flow.

precipitation for the interval. The daily ET rate is the total for the interval divided by the length of interval. Table 4 summarizes the ET estimates for the 5 years of study. Soil water depletion was significantly reduced in the clearcut block, as indexed by the reduced ET rate following harvest (Troendle and Meiman 1986).

The ET rates presented in table 5 appear quite reasonable based on watershed balances. The potential impact of the creation of the opening on the water balance of the site can be estimated by summing the ET savings and the changes in snowpack peak water equivalent. Table 5 presents these estimates for the 3 posttreatment years. They represent conservative estimates of potential change, because any errors in the working assumptions would underestimate the impact. However, the 7.8-inch mean increase in water available for streamflow from the cut area shown in table 4 compares well with the observed increases on nearby Deadhorse Creek for the same time period and for the same percentage of area cut (33%). The 7.8-inch increase estimated on site for the clearcut represents a 2.6-inch increase over the entire study area. This potential increase is similar to the observed increase resulting from a similar harvesting practice on the North Fork of Deadhorse Creek (table 2). The comparison does not include any savings that may have occurred in April and May on the study plot, however.

In 1975, another study was started in 60- to 70-year-old lodgepole pine on the Fraser Experimental Forest to test the effect of different thinning levels on subsequent growth (Alexander et al. 1985). The study area was divided into five blocks, with one block thinned each year. Within each block, four 0.4-acre plots were thinned from below, each to a different growing stock level (GSLs 40, 80, 100, 120 square feet basal area). The first series of plots in block 1 were thinned in 1976; the last series of plots in block 5 were thinned in 1980. Additional plots in blocks 2, 3, and 4 were added in 1981 and thinned to GSL 160. Adequate stands for GSL 160 were not found in blocks 1 and 5.

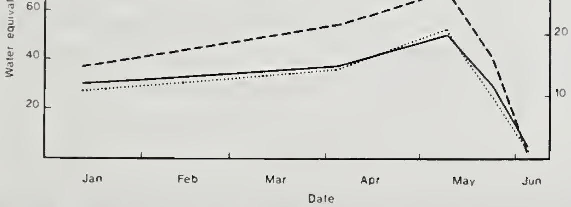

Figure 9.--Snowpack accumulation and ablation on study sites for 1984.

Four neutron-probe access tubes were installed to a depth of 5.5 feet in each GSL plot and on the single control plot in block 2. They were installed later on the 160-level plots selected in 1981. Soil moisture was measured at 6-inch-depth intervals periodically during each growing season from 1976 to 1983. The objective of the study was to define the differences in soil water depletion during the growing season as a function of basal area, block or site differences, and years or climatic differences. One obvious problem with the experiment is that in block 1 there was no calibration or pretreatment data and only 7 years of posttreatment record, whereas on block 5 there were 5 years of pretreatment and 2 years of posttreatment data. All years differed climatically.

Linear regression techniques were used to evaluate causal relationships between the rate of change (±) in soil moisture per unit time (dependent variable) and basal area, block or site, midpoint date of the measurement interval, and precipitation during the measurement interval.

Growing-season precipitation is used primarily on site and does not appear to make a detectable contribution to streamflow (Orr 1969, Troendle and King 1985, Troendle and Meiman 1986). Therefore, a second dependent variable, daily evapotranspiration, was calculated. This was estimated as the sum of the soil water depletion between two successive measurements and the precipitation that fell during the interval, divided by the number of days in the measurement interval. At the plot level, this number represents the best estimate of average daily water use (ET) for the measurement interval.

Daily soil water depletion was regressed on daily precipitation, basal area, date (from January 1 until the midpoint of the measurement interval), and block or site. Basal area was the least significant of the independent variables ($P = 0.01$). When the same regression was fitted for each of the individual years, the significance of basal area in the equation depended on whether it was a wet or dry year. In dry years, basal area was not related significantly ($P = 0.50$) to daily soil water depletion.

Figure 10 represents a plotting for all years of record of basal area over soil water depletion. Basal area is significant when regressed on soil water depletion ($p = 0.001$, $r = 0.22$, $SE = 0.02$ inch), but it is apparent that there is much variation in soil water depletion that cannot be accounted for by basal area alone.

Because each year of the study was different climatically, and because not all plots were treated under the same climatic

Table 4.--Summary of evapotranspiration (inches) estimate for measurement intervals (Troendle and Meiman 1986).

Year	Interval dates	Number of days	Plot 1		Plot 2		Plot 3	
			ET	ET/day	ET	ET/day	ET	ET/day
1981	6/9-7/22	43	4.4	0.10	4.3	0.10	4.7	0.11
1982	7/7-9/8	63	6.8	0.11	7.2	0.11	7.4	0.12
				Harvest				
1983	6/28-10/12	105	12.8	0.12	11.1	0.11	12.5	0.12
1984	6/13-9/27	116	13.1	0.11	11.8	0.10	13.7	0.12
1985	6/4-10/9	127	15.2	0.12	12.9	0.10	16.2	0.13
Aver. ET/day	1983-1985			0.12		0.10		0.12

Table 5.--Estimation of potential change in water balance (inches) following clearcutting (Troendle and Meiman 1986).

Year	ET difference	PWE difference	Minimal change
1983	1.6	4.9	6.4
1984	1.6	6.9	8.5
1985	2.8	5.7	8.5
$\bar{x}$	2.0	5.8	7.8

conditions, it is impossible to present an average soil water depletion curve for each basal area.

In the previous example for the partially cut North Slope (unit 8) portion of Deadhorse Creek, basal area was reduced 35% to 40%, or from 180 to 120 square feet per acre. Estimating the seasonal difference in soil water depletion from figure 10, the savings would be 1 inch for the growing season (June through October). As noted earlier, there also was a 1.9-inch increase in peak water equivalent in the spring snowpack. The 1-inch average savings during the 4-month portion of growing season seems reasonable, considering the total increase in flow was estimated to be 3.6 inches at the streamgage. Because any savings in April and May are not included, the combination of the 1.9-inch winter interception savings and 1.0-inch summer depletion savings represents a reasonable portion of the total (2.9 of 3.6 inches). This is a very speculative extrapolation of plot data that is presented only to show that the numbers are reasonable, and that as we add separate components together, the total is reasonable.

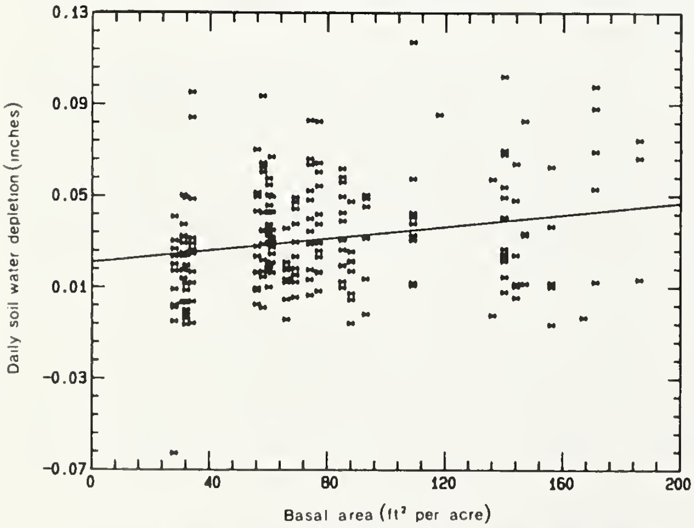

Figure 10.--Relation between daily soil water depletion and basal area.

As noted previously, total evapotranspiration for each soil moisture interval can be estimated by summing the precipitation that fell during the interval with soil moisture depletion (±). This sum represents the maximum amount of water available for ET, and includes any water lost to deep seepage or streamflow. However, because summer precipitation is not significantly correlated with change in flow, summer precipitation is presumed to be retained on site, thereby reducing soil water recharge requirements (and apparent depletion) or evaporation. Soil water depletion differences between the different basal area levels reflects the net effect of the ET changes. Daily ET rates were not presented in a format similar to the daily soil water depletion rates, because the soil water depletion best expresses the change caused by basal area reduction, especially during rain-free periods. ET averaged 0.14 to 0.17 inch per day.

Soil moisture studies, such as this one and others in the subalpine (Potts 1984, Troendle and Meiman 1986), are not designed to estimate ET, although the estimates of daily use appear to be good. The strength of these studies is in their definition of the soil water deficits in the fall as a function of basal area. These recharge requirement differences reflect the effective net change in the ET processes (pertaining to flow) that result from the change in growing stock levels. These differences are the net effect passed on to the increase in flow when recharge begins. Kaufmann et al. (1987) addressed the components of ET that are being impacted.

Summary

The understanding of the relative role of various evaporative components on the water balance has gone full circle. Very

early observers, such as Church (1912), felt that snowpack accumulation pattern and attendant losses were a dominant controller of runoff and that certain stand configurations were superior to others, with respect to accumulation and subsequent runoff. The results of the Wagon Wheel Gap experiment also pointed out the role of summer evaporative processes on the total water balance. Studies in the 1930s and 1940s confirmed the significance of both winter and summer evaporative processes. Then, in an attempt to improve process definition, there was a conceptual shift in understanding toward one of manipulating ET in the growing season, and controlling or modifying input placement and efficiency of delivery in the winter.

However, more recent research has redefined the significance of both summer and winter evaporative losses. Opportunities for manipulating the water balance through density and tree species control have been identified. Snowpack deposition, both the pattern of accumulation and the amount, can be influenced by any form of stand density control, not just clearcutting.

The questions currently being asked in research have a much higher degree of resolution addressing such topics as the effects of stand structure and species composition, as well as physiographic conditions, on overstory/understory evapotranspiration processes during each season of the year.

Current models that simulate the role of forest on the water balance work reasonably well. The next generation model will do similar things, while integrating precipitation and energy on a more site-specific basis.

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2H5

Applying Hydrologic Principles to the Management of Subalpine Forests for Water Supply

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Abstract--WRENSS HP is used to estimate an increase in yield at Fool Creek, Colorado, of 62 mm compared to an actual increase of 67 mm. Similarly, at Cabin Creek, Alberta, WRENSS-HP estimated 7 mm compared to an actual increase of 17 mm. If representative and accurate precipitation data were used, long term actual annual water yields were estimated with no error at either Fool Creek or Cabin Creek. The predicted effectiveness over a 100 year implementation period of 10 ha clear cut blocks as a practice in increasing water yield was virtually identical to that of 1 ha clearcuts if winter wind speeds averaged less that 1 m s^{-1}. At a wind speed of 5 m s^{-1}, the 1 ha clear cut practice produced an increase three times as great as the 10 ha blocks, mainly because of the protection these smaller clearcuts afford accumulated snow from wind and subsequent evaporation.

The management of forests is becoming increasingly complex as various user groups place often conflicting demands upon the same land base. Water users are one such group. Their demands for more water are apparently insatiable.

One of the roles of forest land is watershed. This is a geographical fact that cannot be dismissed. The subalpine forests of the west are among the most important of these watershed as the streams originating on them flow through very arid but valuable agricultural land enroute to the sea.

The virgin forest is not the most efficient watershed in terms of water supply. Many forests can be physically configured, using various clear cut patterns, to make them yield from 20% to 40% more water each year than the uncut condition. Scientists working in the field of forest hydrology have sought to understand the hydrologic system that forests represent and to apply that understanding to the development of management techniques that can be used to provide predictable increases in water yield. My purpose in this paper is to illustrate how the hydrologic procedure presented in the WRENSS handbook (U.S. Forest Service 1980, Troendle and Leaf 1980) can be used to estimate changes in water yield, and the accuracy of the results obtainable with it.

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The Hydrologic Procedure in WRENSS

WRENSS-HP

The WRENSS handbook (U.S. Forest Service 1980) contains a hydrological procedure (Troendle and Leaf 1980) that represents the state of the art for estimating the change in evapotranspiration that will occur when either clear cutting or reforestation occurs on watersheds in the United States and much of Canada (I will call the hydrology portion WRENSS-HP to avoid confusion with the other WRENSS routines.). A change in annual evapotranspiration is a necessary and sufficient condition to affect an eventual (and comparable) change in annual water yield.

Evapotranspiration quantity (ET) is the only portion of a watershed's water balance that we can manage with appropriate forestry practices. WRENSS-HP estimates of evapotranspiration can be used in two ways: (1) directly as estimates of changes in water yield that can be affected by forest cutting; or (2) indirectly within the water balance equation to estimate generated runoff (GRO). The difference in annual evapotranspiration that WRENSS-HP estimates for a forested watershed under uncut and cut conditions is a valid approximation of the change in annual water yield that one can expect from that watershed.

Any land management strategy designed to increase water supply through some form of timber harvest must therefore

reduce evapotranspiration (the amount of water lost to the atmosphere as evaporation from wet surfaces such as the snowpack, leaves, litter and other debris, and from the soil via the stomata on the leaves of trees and other vegetation) if it is to be successful. Contrary to what is often popularly believed, the maximum reduction in evapotranspiration is not generally achieved by removing all of the trees from a watershed. The evaporation process is too complex for such a simple solution. Evapotranspiration is affected by; (1) energy form (e.g. air temperature, solar radiation, wind, etc.), (2) water vapor concentration (e.g. humidity of the air and motion of the air next to any surface with water on it) and (3) water availability (e.g. surfaces, such as leaves or litter, upon which water can accumulate or the proximity of roots to water in the soil). The rearrangement of a forest from one uniformly vegetated to one with discontinuities at tree clearing edges alters all of these. In general, one must reduce the number of trees drawing upon the soil moisture, reduce the total amount of tree canopy, and protect cleared surfaces (and new growth on them) from direct exposure to the sun and wind. The physical configuration of a forest that is to be optimized for supplying water must be carefully crafted and maintained to minimize evapotranspiration.

The WRENSS-HP procedure for estimating evapotranspiration is based on two comprehensive hydrologic models; but WATBAL (Leaf and Brink 1975), is the one most applicable to the snow dominated subalpine forest. The WATBAL model calculates daily ET based on a set of model parameters specific to a particular watershed and daily inputs of precipitation, temperature, etc. The parameters of WATBAL can be adjusted to allow for precipitation (P) and climatic data that may be only indices of true precipitation and climate. The daily values of generated runoff, (GRO) equation [1], that are calculated by WATBAL, can be routed through the storage components of a specific watershed, upon which it has been calibrated, to produce an accurate estimate of each day's streamflow.

$$GRO = P - ET \qquad [1]$$

In contrast, the WRENSS-HP procedure estimates seasonal evapotranspiration as a function of seasonal precipitation within a broad climatic region. It contains no parameters to adjust for indexed precipitation. Nor does it contain watershed descriptors that would allow one to calculate changes in storage (ΔS). Since it contains no provision for estimating storage, nor changes in storage, it cannot be used to estimate the amount of water (routed streamflow) that will be present in a stream channel at any given time. The role of storage is somewhat clearer in the alternate form of the definition for generated runoff, equation [2], where water yield (Y) is streamflow divided by watershed area.

$$GRO = Y \pm \Delta S \qquad [2]$$

With WRENSS-HP, an estimated change in generated runoff for a year or possibly even several years, will generally not be directly verifiable as a change in measured water yield, as the measured yield may be influenced by the unknown magnitude of change in watershed storage. Clearly, generated runoff (eq. [2]) is equal to water yield only when S is zero. In fact, the only circumstances under which GRO, as calculated from WRENSS HP evapotranspiration estimates and equation [1], will equal annual yield or streamflow are: (1) The precipitation data must be accurate for and representative of the watershed under consideration; (2) Changes in storage must equal zero or be averaged over a sufficiently long time period so that their algebraic sum is zero. Although the authors of WRENSS HP suggest that it can be used to estimate both seasonal and annual evapotranspiration, only the annual estimates are verifiable within the water balance equation [1] (within the limits imposed by changes in annual storage). Because of short term storage in the snowpack and soil, the WRENSS HP estimates of seasonal evapotranspiration can only be verified by on-site measurements of seasonal evapotranspiration. Thus one should generally consider the seasonal ET estimates only as intermediate steps in the estimation of annual evapotranspiration.

Availability of WRENSS HP

The complete WRENSS handbook is available from the U. S. Environmental Protection Agency (U.S Forest Service 1980). The nomograms in the hydrology chapter (Troendle and Leaf 1980) can be used to calculate annual evapotranspiration under various forest cutting options. I digitized the nomograms for the snow dominated regions, fitted them to second order equations, and prepared an interactive program for the Hewlett Packard 9825A calculator. These equations have since been used to produce interactive programs for an IBM PC/XT or compatible microcomputers (Bernier 1986). The microcomputer version is the easiest to use, but it may give results slightly different from the nomograms as the snow accumulation and snow evaporation routines are not exactly the same as those published in the EPA handbook.

How to Use WRENSS HP

In order to estimate changes in water yield that can be expected to occur under a forest management scheme, WRENSS-HP is used to calculate the annual evapotranspiration for some baseline condition (usually fully treed), and under the same overall precipitation regime but with some de or re forestation. The difference between the two values is the estimated change in annual yield. In partially clear cut situations, WRENSS-HP apportions differing amounts of precipitation to the cut and treed areas on the following bases:

1. In clearcuts, with maximum windward dimensions less than approximately 15 tree heights, snow accumulates preferentially, presumably at the expense of the surrounding treed area;

2. In clearcuts with windward dimensions greater than 15 tree heights, snow may be removed from a clearing by wind and either sublimate while in transport or be redeposited in the downwind treed areas; this transport can be switched off in our microcomputer versions (Bernier 1986);
3. If the surface of a clear cut is aerodynamically rough, then snow may be retained in place regardless of the windward dimensions.

Some evaporation may occur in situ from the surface of the snow accumulated within a clear cut. In our microcomputer versions of WRENSS-HP (Bernier 1986) evaporation from snow occurs as a function of the wind speed in the clear cut. Our studies have shown that the wind speed 2 m above the surface of clearcuts greater than 20 tree heights across is the same as would occur at either 10 m above the canopy or in completely open situations. In clearcuts smaller than 20 tree heights across, wind speed and evaporation from the snow surface in the clear cut is reduced as a function of clear cut dimensions.

Data Requirements for WRENSS-HP

Land managers have considerable latitude in the use of WRENSS-HP to estimate treatment effects on annual yields. Site specific climatic and streamflow data are not always necessary. A current inventory of timber volume is desirable, but by no means necessary, as estimates by knowledgeable personnel are quite sufficient in most instances.

First Year or Initial Effects

Precipitation by WRENSS-HP season[2].--The distribution of precipitation between seasons is more important when WRENSS-HP is used solely to estimate changes in annual yield than is the absolute amount of precipitation. The amount and representativeness of the precipitation data are of paramount importance in one wishes to estimate actual annual water yield. We have used 5 to 10 year averages or the precipitation from the years with the highest and lowest annual streamflow and noted little effect on estimated change in annual water yield (Swanson and Bernier 1986). These data can be obtained from something as simple as an hydrologic atlas for the area that has isopleths of mean annual precipitation and mean annual water yield. Any reasonably local precipitation station's data can be used to apportion annual precipitation among the percentages applicable to the WRENSS-HP seasons.

[2]The months used in the WRENSS HP procedure's seasons do not correspond to the normal winter, spring, summer and fall periods, although they use the same names!

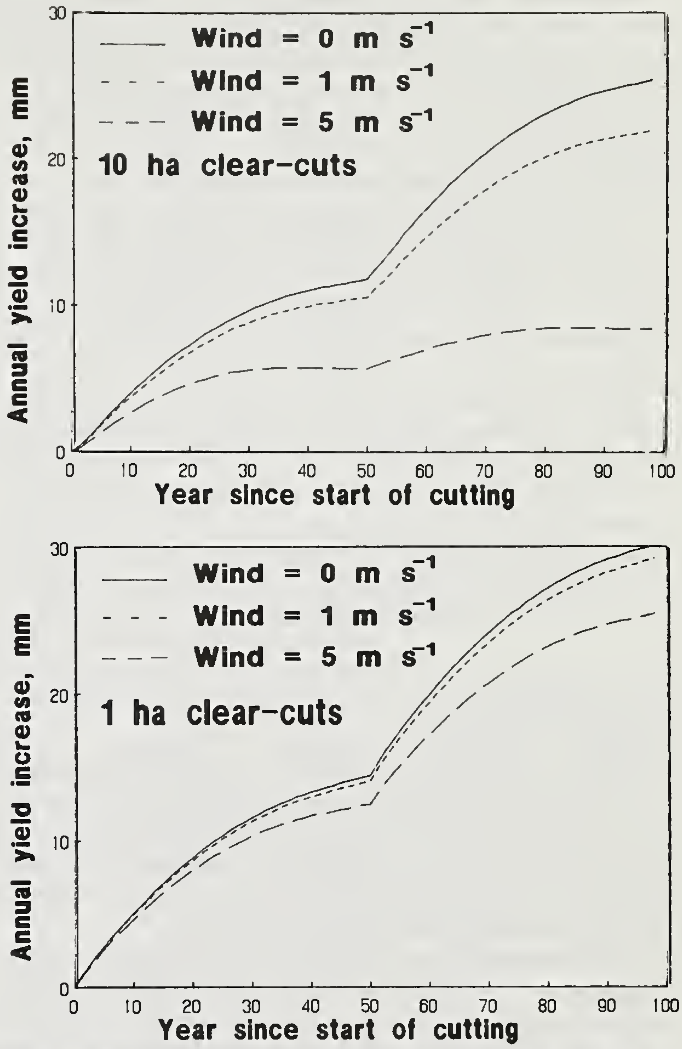

Figure 1.--Progressive effect on annual water yield of annual clear cutting of alternate blocks of mature subalpine spruce-fir forest at 50 year re entry intervals on a watershed throughout a 100-year rotation. With winter wind speeds (October to April) of 1 m s^{-1} or less, the 10-ha clear cut blocks (a) produce only a slightly lower increase in yield when fully implemented than the 1-ha blocks (b). However, the difference in the effectiveness for increasing water yield of the two clear cut sizes becomes much more noticeable when winter wind speeds are much greater than 1 m s^{-1}.

An estimate of average wind speed during the winter and spring.--The windiness of a site has a very marked effect on evaporation of snow (fig 1a). If wind speeds are generally less than 1 m s^{-1}, then wind speed can be ignored (fig 1). If no values for wind speed are available, then one can estimate effects for a range of values and try to verify the actual speed at some later time. If in doubt, it is best to use smaller clearcuts as the surrounding trees protect the snow surface from wind, and ensure higher water yields (fig 1b).

The tree species present, its height and the basal area for a full occupancy (mature?) stand.--This is not critical as estimates of evapotranspiration are made using fractions of this value rather than the absolute quantity.

Basal area that might remain within a clear cut after clearcutting.--In Canada and probably in the United States, some tree species are not considered to have sufficient value to harvest, and are left standing. These generally occupy less than 15% of the total area of any given clear cut, but may need to be taken into account.

The type of treatment, or in the case of clear cutting, the size of clear cut, either in dimensions or as an area.--Our microcomputer version of WRENSS-HP queries one for the clear cut dimension parallel to the prevailing wind direction (Bernier 1986). If this information is not available, then the program calculates it as if it was a square clear cut block of the given area.

The area to be treated and the total area of the watershed.--If the estimates are not for a specific location, then use some convenient unit area.

The general topographic aspect of the area under investigation.--We use east west aspects if no site specific information is available. WRENSS-HP produces considerably different yield estimates for north and south aspects, so if these are known to apply, they should be used.

Effects Throughout a Rotation

Rate of height and basal area regrowth.--We have used a linear function from 0 to maximum height or basal area over the proposed rotation duration to produce the estimates in figure 1. If local data for growth are available, they can be input on a year by year basis to estimate the effect of regrowth on the change in water yield that will occur each year.

The amount of new cutting that will occur and at what frequency.--For example, areas to be harvested in Canada are delineated and divided into a number of areas to be cleared each year. If subsequent cuts in the same watershed are made at five year intervals, than new clearcuts should be introduced into the calculations at five year intervals throughout the rotation.

Mode of implementation.--If a forest is clear cut in an alternate block manner where the treed block between clearcuts are removed at some later time period, the time when these trees are to be removed relative to the state of regrowth in any adjacent clear cut blocks must also be considered.

For example, in Alberta, an area to be managed as one unit within a 100-year rotation is subdivided into 5 compartments. The second and subsequent compartments are not entered until all of the timber from prior numbered compartments has been removed. All of the trees in a compartment are removed during a 20 year period, half in the first 10 years, the uncut intervening blocks in the second 10 years. The second entry to remove the intervening treed blocks creates clearcuts that are surrounded by trees 1 to 2 m tall compared to the original forest at 20 m tall and thus less under the wind speed reduction influence of their surroundings than those clearcuts of the first entry.

Examples Using WRENSS HP

Perhaps the best way to demonstrate the WRENSS HP procedure is to show how it has been applied in various situations. I have chosen as examples the Fool Creek watershed near Fraser, Colo., and the Cabin Creek watershed near Banff, Alberta. Both watersheds are in the subalpine zone. The vegetation on both is primarily spruce fir and lodgepole pine. Both have been partially harvested and the effect of that harvest on streamflow is known. The harvest in small clearcuts at Fool Creek has produced an increase of 89 mm (1956 to 1972, Alexander and Watkins 1977); the commercial sized clearcuts at Cabin Creek 17 mm (1975 to 1984, Swanson et al. 1986).

Precipitation data from two sources are available for both watersheds; the Fool Creek tower and Fraser Experimental Forest headquarters for Fool Creek, the CON 5 station and that from two higher elevation stations weighted in accordance with the Thiessen polygon method, on Cabin Creek. Most of Fool Creek's precipitation occurs between October and May (table 1), most of Cabin Creek's precipitation occurs between February and June (table 2). Their subsurface storage volume is quite different as Fool Creek is on granitic material with a shallow porous mantle (approximately 1 m thick); Cabin Creek on sedimentary material with a porous mantle 6 to 8 m thick.

Change in Estimated Yield as Affected by Source of Precipitation Data

One of the common desires of those using WRENSS-HP is to check its output against measured values. The closeness of any comparison of actual and estimated change in annual water yield or in total annual water yield is influenced by both the representativeness of the precipitation data used and any water stored on a watershed which may appear as streamflow in the next or subsequent years. Differences between WRENSS-HP estimated and measured changes in yield are not particularly affected by the precipitation data used, as long as it is from the same vicinity. For example if the Fraser Experimental Forest headquarters site precipitation data is used to estimate the change in water yield on Fool Creek, the mean value predicted, 58 mm compares favorably the 62 mm (table 3) obtained with the Fool Creek wind tower data. However, the total annual flow predicted with the headquarters data is only 203 mm compared to the 318 mm predicted with the wind tower data (table 3). The differences are more evident on Cabin Creek. When CON 5 precipitation is used in WRENSS HP, the total yield and change in annual yields predicted (table 3) are 195 and 11 mm versus 317 and 7 mm if the Thiessen polygon weighted precipitation data are used (actual annual flow 1975 1984 and calculated increase were 316 and 17 mm, Swanson et al 1986). Although the predicted yield increase is only 40% of actual on Cabin Creek, they are both of the same order of magnitude and neither the predicted

Table 1.--Seasonal[1] precipitation (mm) (Haeffner 1971) and measured annual water yield at Fool Creek, Fraser Experimental Forest, Colorado.

Year	FEF headquarters			Fool Creek wind tower			Annual	
	Winter	Spring	Summer	Winter	Spring	Summer	Yield	Change[2]
1967	200	186	114	263	236	97	280	79
1968	181	131	111	249	176	127	232	48
1969	185	243	136	237	268	132	308	64
1970	264	172	130	350	204	168	376	53
1971	262	169	98	360	226	123	401	91
Mean	218	180	118	292	222	130	319	67

[1]Seasons are: Winter, 1 Oct-28 Feb; Spring, 1 Mar 30-Jun; Summer, 1 Jul-30 Sep.

[2]Change in water yield as estimated by paired basin analysis (Alexander and Watkins 1977).

Table 2.--Seasonal[1] precipitation (mm) and measured annual water yield at Cabin Creek subbasin, Marmot Experimental Watershed, Alberta.

Year	CON 5 Station			Thiessen Polygon weighted[2]			Annual	
	Winter	Spring	Summer	Winter	Spring	Summer	Yield	Change[3]
1977	119	253	221	123	276	259	212	-13
1978	137	235	168	185	336	226	335	-2
1980	218	302	221	146	348	272	377	53
1981	189	362	123	236	421	146	503	103
1983	130	243	165	137	294	185	247	7
77-83[4]	159	279	180	165	335	218	335	30
75-83[4]	175	247	184	-	-	-	316	17

[1]Seasons are: Winter, 1 Oct 28-Feb; Spring, 1 Mar-30 Jun; Summer, 1 Jul-30 Sep.

[2]Data from Davies and Kallenbach (1985).

[3]Change in yield as estimated by paired basin regression (Swanson et al. 1986).

[4]Precipitation data for 1979 and 1982 not included because streamflow is not available for these years.

Table 3.--Estimated and measured values (mm) of long term annual water yield and change in annual water yield with harvest at Fool Creek, Colorado, and Cabin Creek, Alberta. Period of record: Fool Creek/FEF Headquarters, 1965-1971; Cabin Creek, 1975-1983 (1979 and 1982 omitted).

Source of data	Seasonal precipitation			Yield		Change in Yield	
	Winter	Spring	Summer-Fall	Predicted	Actual	Predicted	Actual
FEF HEADQUARTERS	218	180	118	203	319	58	67
FOOL CREEK TOWER	292	222	130	318	319	62	67
CABIN CREEK, CON-5	168	252	187	195	316	11	17
Thiessen POLYGONS	207	314	226	317	316	7	17

nor the actual water yield increases are physically significant to water supply.

The proper choice of precipitation data often is a problem in using WRENSS-HP or any water balance procedure. We rarely have the wealth of data available for both Fool Creek and Cabin Creek. As indicated above, precipitation data from nearby stations is probably suitable for use in WRENSS-HP to estimate changes in annual yield. However, the precipitation data ordinarily available will rarely be representative of the watershed in question, even if it is collected on it. Precipitation stations are often located near a stream gauge which is always at the lowest elevation on a watershed. Since precipitation generally increases with elevation, the precipitation measured at the topographic low will normally be less than that occurring at higher elevations on the watershed. Thus WRENSS-HP estimates of actual annual yields obtained from the water balance equation [1] will generally be less, (often much less as with CON 5 data from Cabin Creek) than measured.

Change in Estimated Yield as Effect by Storage

One should not expect either the change in yield or the total yield for any single year to match that actually measured. Year to year variation in estimated and actual changes in water yield should be expected, especially in watersheds with considerable storage, e.g. Cabin Creek, table 4, all years shown. However, even at Fool Creek, which has almost no storage, the predicted and measured changes in water yield for a given year differ rather widely, e.g. table 4: 53 mm versus 79 mm in 1967; 58 mm versus 48 mm in 1968.

Since changes in storage have such a strong effect on comparisons of measured versus actual data, what period of time should one use to perform such comparisons? I suspect that 5 to 10 years of data should be sufficient.

Discussion

Once one has established a proper forest configuration to minimize evapotranspiration, then the increased volume of water that can be extracted from a watershed is directly proportional to the area of the watershed so treated. Our ability to predict water yields that would occur in the absence of treatment is insufficient to detect increases after treatment that are smaller than about 20%. However, this is a measurement problem, and should not be used as an excuse to not manage for increased yield.

The slow growth of subalpine forests makes water yield increases fairly permanent. The same slow growth may make it almost impossible to restructure a forest for water yield improvement after it has be cleared in some less than optimum manner. For instance, if the best water yielding practice is found to be a 50-50 patchwork of 1-ha clearcuts, than a prior harvest in clearings larger than this will preclude an optimum restructuring for most of the rotation period. However, portions of the forest that have not been harvested can be configured in the optimum arrangement.

Small clearings and windthrow are always a subject of considerable discussion among foresters. Full wind speeds develop 10 to 15 multiples of the height of an object downwind

Table 4.—Effect of year to year carryover storage on estimated and measured values of annual water yield and change in annual water yield with harvest at Fool Creek, Colorado, and Cabin Creek, Alberta.

	WRENSS-HP estimates			Measured			
Year	Wind (m/s)	Uncut (mm)	Cut (mm)	Change[1] (mm)	Yield (mm)	Change[2] (mm)	A/P[3]
Fool Creek - Precipitation data from Fool Creek Tower							
1967	3.5	235	288	53	280	79	0.97
1968	3.4	176	234	58	232	48	.99
1969	3.7	246	303	57	308	64	1.02
1970	4.4	321	389	68	376	53	.97
1971	5.1	324	390	66	401	91	1.03
Cabin Creek Precipitation data weighted by Thiessen Polygons							
1977	4.0	228	239	11	212	-13	0.89
1978	4.0	309	316	7	335	-2	1.06
1980	4.0	329	337	9	377	53	1.12
1981	4.0	382	383	1	503	103	1.31
1983	4.0	192	201	9	247	7	1.23

[1]Change is WRENSS HP estimated cut uncut water yield.

[2]Change is as estimated with paired basin regression (Fool Creek: Alexander and Watkins 1977; Cabin Creek: Swanson et al 1986).

[3]Actual measured streamflow after clear cutting divided by WRENSS HP estimated flow after clear cutting.

from it. The leeward edge of clearings greater than 10 to 15 tree heights across should therefore be the most vulnerable. On Fool Creek, where clearings ranged from 1 to 6 tree heights across, little blowdown occurred (Alexander 1967). I think that the Fool Creek results are indicative of what one should expect elsewhere provided the uncut stand is wind firm. With small clearings such as at Fool Creek, one must be careful in locating cutting boundaries if he wishes to take advantage of terrain situations that limit windthrow.

Watershed management cannot be effectively planned and implemented without the involvement of individuals trained in forest hydrology. There will always be a great deal of judgment in any management prescription. Research has provided good tools, but they are not "cook book" techniques. The application of methods to optimize timber harvesting patterns in specific watersheds must always be conditioned by local climatic and topographic conditions.

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Natural and Anthropic Factors as Determinants of Long-term Streamwater Chemistry

Robert Stottlemyer[1]

Abstract--Watersheds of the Fraser Experimental Forest have >30-year hydrologic records and 10 years of stream chemistry data. Seasonal precipitation inputs of K^+ and NO_3^- may affect stream chemistry, but H^+ inputs do not. Long-term stream ion concentration trends appear related to surface water passing through soil macropores. Tree removal has a pronounced effect on increasing watershed NO_3^- loss.

The use of ionic balances is a valuable tool to assess impact of natural and man-caused disturbance. However, much research is needed to identify those factors or processes responsible for natural variation in ion budgets and relationships between ionic concentration and streamwater discharge. A number of recent studies discuss ion dynamics in a watershed ecosystem context (Likens et al. 1977, Bond 1979, Lewis and Grant 1979, Driscoll et al. 1987, Stottlemyer and Troendle 1987). While input/output budgets can indicate ecosystem processes and responses to natural and anthropic disturbance, they are limited in defining cause-effect relationships. Few studies describe the relationship of streamwater discharge to ionic concentration in undisturbed watershed ecosystems with simple annual discharge patterns such as at the Fraser Experimental Forest in Colorado. By "simple" is meant an annual hydrograph dominated by one peak resulting from snowpack melt.

Four watersheds in the Fraser Experimental Forest have long-term (> 30 yrs) hydrologic records, about 10 years of streamwater chemistry, and long-term snowpack data. Precipitation shows only minor evidence of contamination. These attributes provide a base for examining possible mechanisms responsible for observed change in streamwater chemistry and discharge.

This paper looks for watershed responses to natural and controlled human disturbance as indicated by change in streamwater chemistry and watershed input/output budgets. The data are largely preliminary, taken from studies currently underway. Four questions in particular are examined: (1) In small, high elevation Rocky Mountain watersheds significant long-term trends in streamwater ionic concentration can be induced by the timing of snowpack moisture loss and soil perturbation by freeze-thaw (Stottlemyer and Troendle 1987). (2) Despite considerable variation in input/output ratios and stream ionic concentrations, general patterns of nutrient concentration and flux occur during large increases and decreases in stream discharge. (3) When annual peak snow melt is preceded by a small initial release (10+ cm H_2O) the soil water table is raised sufficiently so that subsequent major melt passes through near-surface soil macropores (Driscoll et al. 1987). The chemistry of this meltwater reflects that derived from contact with soil exchange sites, decomposition products, and possibly solutes within the snowpack. Variation in the pattern of snowpack melt has significant effects on annual watershed discharge of ionic species independent of annual precipitation or streamwater discharge. (4) The effect of anthropic disturbance on small basin ionic yield, as through small plot or partial cutting, is considerably influenced by plot size, its effect on snowpack accumulation and timing of melt, and topographic aspect of the basin.

Site Description

The Fraser Experimental Forest, established in 1937, is about 137 km west of Denver, Colo. A detailed description of the experimental watersheds can be found in Stottlemyer and Troendle (1987) and Alexander and Watkins (1977). Soils descriptions and maps are provided by Retzer (1962). Four primary watersheds are currently under study: Fool Creek, East St. Louis, Lexen and Deadhorse. This paper mainly addresses data from the conterminous Lexen (127 ha) and Deadhorse (278 ha) watersheds (fig. 1).

Road building in the Deadhorse watershed began in 1970-71 with construction of access roads to the North Fork and Upper Basin weir sites. Additional access and spur roads (2.8

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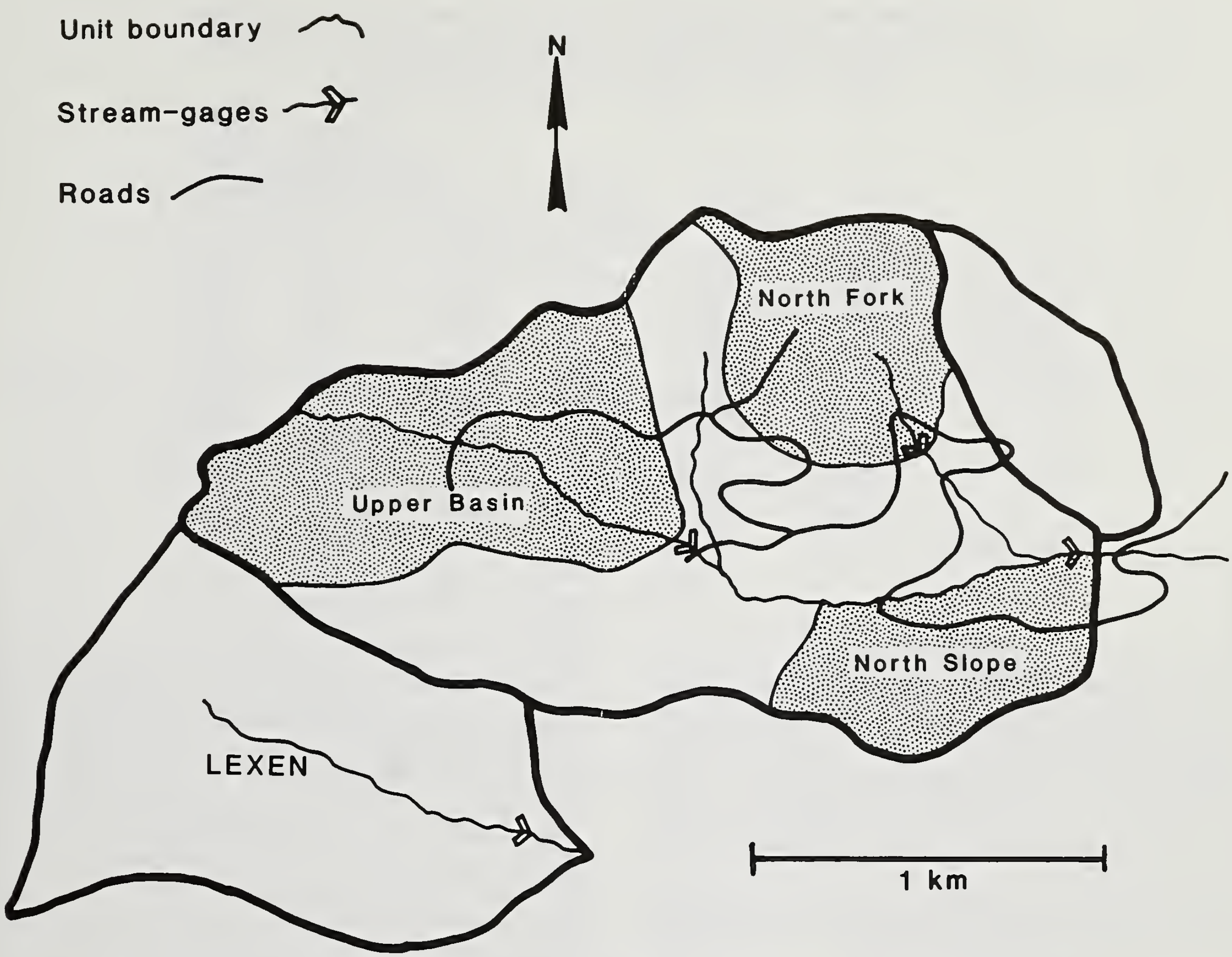

Figure 1.--The Lexen Creek and Deadhorse Creek watersheds and subbasins, Fraser Experimental Forest.

km) were built in 1976 to harvest the North Fork, 2.4 km were built in 1977-78 to harvest the North Slope, and 3 km built in 1981 to harvest the Upper Basin. Total area disturbed in road building was 9 ha (Troendle and King 1986). The first subdrainage timber cutting occurred in 1977 in the North Fork. This was followed by harvesting the North Slope in 1980-81, and the Upper Basin in 1983-84. Additional details of the treatments can be found elsewhere (Troendle and King 1986).

Methods

Streams have been sampled in 1965, 1970-71, and 1982-1987. Streams were sampled just above the gaging station (120° "V" notch weir, digital stage height recorder) and stilling pond (concrete base and weir support, log walls) on a weekly basis from approximately late April to October. On occasion streams have been sampled during winter, but streamwater discharge is so low (mean 0.02 $L \cdot s^{-1} \cdot ha^{-1}$) and unchanging that intensive winter sampling is usually not warranted.

Filtered (0.45 μm) samples are sent refrigerated to Michigan Technological University for ion determinations. Cations and anions are analyzed on an automated Dionex Model 2020 ion chromatograph (IC). Details of quality assurance procedures, field sampling procedures and laboratory analyses are documented elsewhere (Stottlemyer 1987a, Stottlemyer and Troendle 1987).

Precipitation quality is measured weekly at the Experimental Forest Headquarters using an Aerochem Metrics event precipitation collector. Field sampling follows the National Atmospheric Deposition Program (NADP) protocol. Samples are processed in the same manner as stream samples. Daily precipitation quantity is recorded by use of a standard Belfort recording raingage. An additional Aerochem collector was installed at the top of the Lexen watershed in 1987.

Over 20 years of snow course data exist for the major watersheds. In 1985 we began to monitor snowpack chemistry at peak moisture content and with snowpack aging. To date monitoring has been confined to the Lexen, Deadhorse and Upper Fool or Alpine watershed. Change in snowpack ionic content during spring melt has been monitored in proximity to the weather station at Experimental Forest Headquarters. In 1980 snow monitoring plots were established in mature spruce-fir near West St. Louis Creek. The objective of this

Table 1.--Mean annual precipitation ion input (eq + ha^{-1}) for period 1984-86 for the Fraser Experimental Forest and National Atmospheric Deposition Program (NADP) stations in the state of Colorado.

Ion	Fraser	Mesa Verde	Sand Spring	Manitou	Rocky Mtn. Lock Vale	Rocky Mtn. Beaver Meadow
Ca^{+2}	104(103)	258(613)	128(245)	96(135)	177(188)	80(84)
Mg^{+2}	35(49)	43(55)	39(80)	29(40)	57(70)	26(30)
K^{+}	32(37)	8(12)	7(15)	8(13)	14(19)	9(19)
Na^{+}	60(75)	40(64)	40(100)	28(38)	64(91)	33(47)
NH_4^{+}	40(35)	48(56)	54(62)	48(72)	102(146)	62(76)
H	62(56)	80(105)	39(50)	47(47)	109(109)	48(65)
NO_3^{-}	82(48)	114(98)	104(128)	108(121)	194(190)	91(72)
SO_4^{-2}	113(81)	195(196)	140(184)	116(118)	261(232)	113(97)
Cl	54(47)	32(41)	30(54)	22(31)	51(48)	25(29)
Mean Cm ppt	67(25)	54(9)	43(3)	40(7)	117(12)	44(2)
N	81	135	144	128	127	142

study was to look at the effect of four-tree length openings on snowpack accumulation. Three 1-ha conterminous plots, one cleared (treatment), one upwind (control), and one downwind of the cleared plot have been monitored. Each plot has a grid of 15 snowpack sampling stations. In early April 1987, we sampled all stations for snowpack moisture and ionic content. Our objective was to estimate canopy modification of snowfall quality and quantity.

The computation of input/output budgets for dissolved inorganics and the statistical methods used are detailed elsewhere (Stottlemyer and Troendle 1987).

Results and Discussion

Precipitation and Streamwater Chemistry

Calcium is the dominant cation and SO_4^{-2} the dominant anion in incident wet precipitation (table 1). Concentrations of H^{+}, NH_4^{+}, NO_3^{-}, and SO_4^{-2} are quite low while K^{+} is high in concentration relative to NADP stations in Colorado.

Volume-weighted concentrations of ions in precipitation change little seasonally (fig. 2). Potassium and NO_3^{-} show the most increase in summer (July - September). The increase is sharpest for K^{+} which suggests increased precipitation concentration due to gains in airborne dust following regional loss of snowpack. Hydrogen and SO_4^{-2} reach highest concentration in February and December respectively. Precipitation concentrations of Ca^{+2} and K^{+} equal those of NO_3^{-} and SO_4^{-2} except in late winter when the H^{+} input reaches its maximum.

Precipitation concentration and input of all ions except K^{+}, H^{+} and NO_3^{-} are small relative to stream concentrations and output. The relatively low input of H^{+} to these watersheds is retained in the terrestrial component (Stottlemyer and Troendle 1987). The low streamwater acidity reflects the strong buffering capacity of terrestrial components. On an annual basis K^{+} input is conserved and NO_3^{-} input strongly conserved (Stottlemyer and Troendle 1987).

Precipitation inputs to Lexen Creek are about 20% greater than for Deadhorse due to the higher mean elevation of Lexen (C. Troendle, US Forest Service Rocky Mountain Forest and Range Experiment Station, personal communication). However, annual discharge from Lexen exceeds Deadhorse Creek by 43% (Troendle 1983) which probably reflects increased evapotranspiration from Deadhorse with its lower mean elevation.

The annual cycle of streamwater discharge dominates trends in volume-weighted streamwater chemistry (figs. 2 - 5). Daily within-stream ion concentrations generally are most variable during high spring streamwater discharge (figs. 2 and 5). This is especially true for H^{+} and NO_3^{-} (fig. 2). Potassium, H^{+} and SO_4^{-2} are the most variable earlier in the snowpack melt period (fig. 6). Summer storms are rarely reflected in watershed hydrographs (fig. 5) and have little or no effect on streamwater chemistry. Processes that may affect seasonal streamwater ionic concentrations, but which have not yet been specifically examined, include the following. High NO_3^{-} concentrations in spring precipitation could affect stream NO_3^{-} concentrations during snowpack melt, and the late summer precipitation concentrations could be reflected somewhat in fall stream chemistry. Lowered biological activity in fall could complement precipitation concentrations and help account for the observed increase in stream NO_3^{-} concentration.

The year-to-year variability in snowpack amount, density, and freeze-thaw period is considerable. From 1970 to 1986 snowpack moisture content in Lexen Creek on or near April

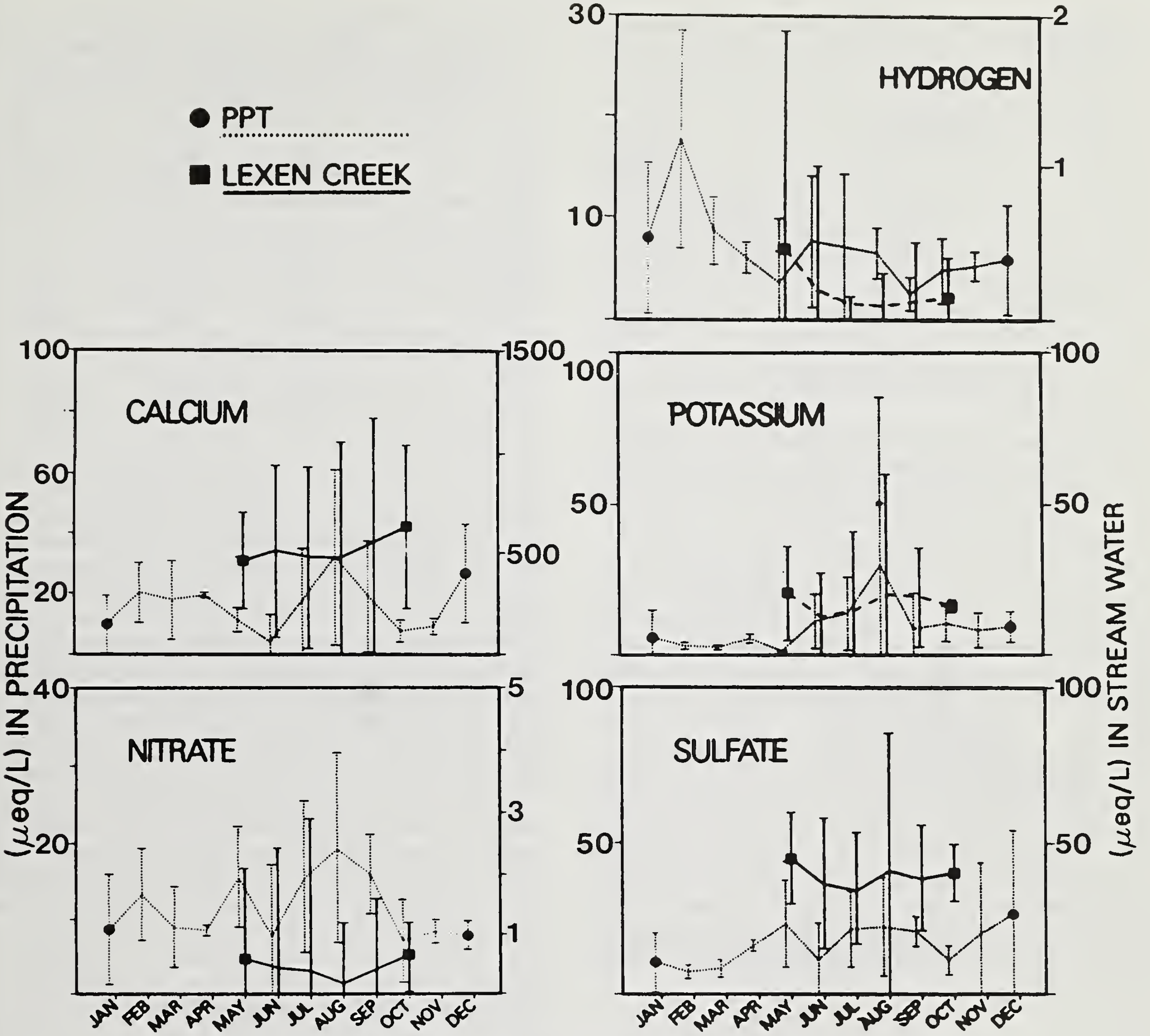

Figure 2.--Volume-weighted mean monthly concentrations for selected ions in wet precipitation (1983-86) and Lexen Creek streamwater (1982-86), Fraser Experimental Forest. The vertical lines for each month represent one standard deviation.

1, the date of estimated mean maximum snowpack moisture content, has varied from 16.6 to 61.5 cm H_2O with a mean of 40.2 ± 11 cm. Ion concentration in snowcores collected in openings near Headquarters from 1984 - 1986 averaged 20 ± 21, 2.5 ± 2.5, 4.9 ± 3.4, 5.7 ± 3.1 and 7.9 ± 8.2 $\mu eq \cdot L^{-1}$ for Ca^{+2}, K^{+}, H^{+}, NO_3^- and SO_4^{-2}, respectively.

The forest canopy is a major factor in altering both the quantity and quality of snowfall reaching the forest floor (Fahey 1979, Cadle et al. 1984). In the snow plots adjacent to West St. Louis Creek, sampled in late March 1987, canopy interception of snowfall amount was 38% (table 2). Despite such interception, throughfall solute addition to incident precipitation resulted in K^{+} and H^{+} solute loads in the snowpack beneath the forest canopy exceeding those of the clearing. Weighted ion concentration of $K+$, $H+$, and SO_4^{-2} in snowpack beneath the forest canopy exceeded that in the opening.

Snowpack solute content and especially snowpack melting patterns affect trends in streamwater chemistry and ion output (Driscoll et al. 1987, Fahey 1979). At Fraser Experimental Forest change in streamwater ionic concentrations of Ca^{+2} from 1965 through 1986 show a significant increasing trend ($p<0.01$, Kendall's tau, figs. 4 and 5). There was a similar

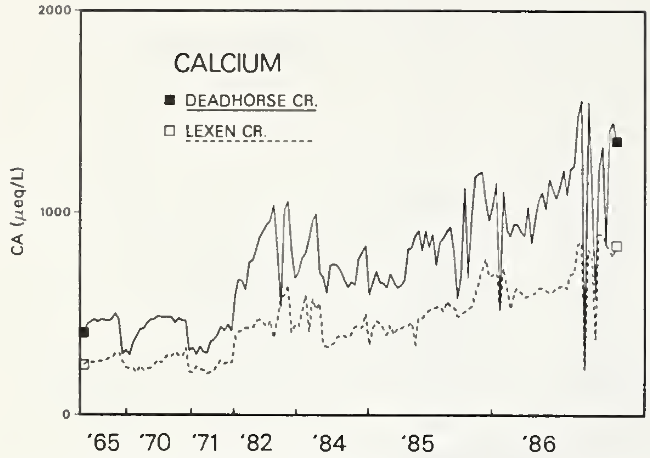

Figure 3.--Time trend of Ca^{+2} concentration ($\mu eq \cdot L^{-1}$) for Deadhorse and Lexen Creeks for the period of study.

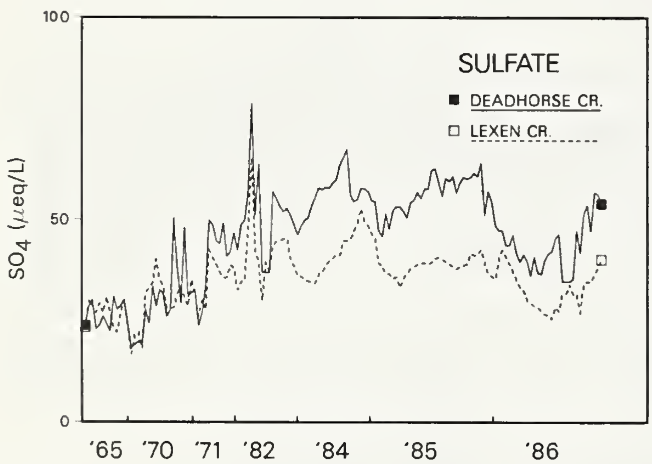

Figure 4.--Time trend of SO_4^{-2} concentration ($\mu eq \cdot L^{-1}$) for Deadhorse and Lexen Creeks for the period of study.

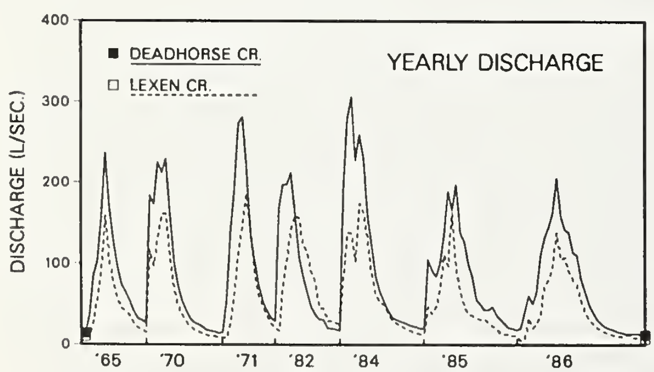

Figure 5.--Stream discharge ($l \cdot s^{-1}$) from Deadhorse and Lexen Creeks from May to September for years shown.

Table 2.--Ion concentration ($\mu eq \cdot l^{-1}$) and snowpack content ($eq \cdot ha^{-1}$) for selected chemical species, snow plots on Short Creek adjacent West St. Louis Creek, March 31, 1987. D = downwind plot, T = treatment (clearcut), and C = control or upwind plot.

	Downwind	Treatment	Upwind
Amount (cm H_2O)	15.8 . 3.9	26.8 . 2	17.5 . 4.5
Volume-weighted mean concentration:			
K^+	10.2	4.6	7.7
H^+	4.8	2.3	4.5
NO_3^-	4.6	7.6	2.6
SO_4^{-2}	11.0	9.4	10.6
Snowpack content (eq/ha)			
K^+	16.2	12.3	13.4
H^+	7.5	6.1	7.8
NO_3^-	7.3	20.2	4.5
SO_4^{-2}	17.4	25.1	18.6

significant trend for SO_4^{-2} up through 1985. There has been no significant trend in precipitation amount or streamwater discharge over this period. This trend in streamwater chemistry appears to be related to natural factors, in particular the pattern of snowpack melt and the relationship of ion concentration to streamwater discharge. The years 1984 and 1986 are included in this trend in ionic concentration yet peak and total annual runoff in 1986 was but a fraction of 1984. This suggests that these two variables, peak snowpack moisture content and total annual runoff, are not major factors responsible for the observed trend in stream ionic concentration. However, in both 1984 and 1986 prior to any increase in stream discharge there was a rise in groundwater level (Troendle, unpublished data). I present the following possible explanation. Spring runoff consists of water from two sources: (1) an initial high ion concentration mini-pulse as the first melt water raises the groundwater stage slightly increasing, through piston action, its flow into the stream, and (2) streamflow dominated by lateral movement in near-surface soil macropores. The chemistry of this second phase is dominated by ions (Ca^{+2}, NO_3^- SO_4^{-2}) released from mineralized organic material and exchange sites in near-surface soils. The relationship between ion concentration and stream discharge changes with change in melt water pathway. This appears to be the process underway in other regions also (Driscoll et al. 1987, Stottlemyer 1987b).

In sum, it appears possible that the significant long-term trends observed in both weighted and unweighted (see Stottlemyer and Troendle 1987) stream ionic concentrations of Ca^{+2} and SO_4^{-2}, and the variation seen in total annual cation discharge versus total annual streamwater discharge (Stottlemyer and Troendle 1987) are due principally to the relationship between stream ionic concentration and discharge. And this relationship is much influenced by any snowpack melt pattern which maximizes water passage through soil macropores. This subject is the focus of continuing ongoing research at the Fraser Experimental Forest.

Factors Regulating Stream Ionic Concentration Patterns

To obtain additional understanding of possible factors regulating stream ionic concentrations, I plotted ion concentration against streamwater discharge by date for 1985-86 in Lexen and Deadhorse Creeks (fig. 6, only 1986 Lexen data shown). Most of the annual variation in ion concentration appears related to change in streamwater discharge. Immediately preceding snowpack melt in 1985 and 1986, streamflow appeared to continue a slight decline and ionic concentration to increase (fig. 6). This ion concentration increase probably reflects the decline in stream water discharge, but regressions of ion concentration against stream water discharge do not account for all the concentration increase (Stottlemyer and Troendle 1987). It is probable that some initial snowpack melt, through "piston action" on deeper soil water, forced a pulsed ionic input from groundwater to the stream without a proportional increase in runoff. Except for Ca^{+2} all ions produced a clockwise plot by date with higher concentrations during the rising hydrograph than during its recession. As a percentage of mean ionic concentration NO_3^- showed the greatest difference between the rising and falling sides of the annual discharge curve followed by K^+ and SO_4^{-2} (fig. 6). Summer and early fall variation for K^+ and NO_3^- may be reflecting change in biological uptake of these ecologically important ions. The SO_4^{-2} trajectory, which for 1986 is unique among the ions analyzed, appears to be reflecting simple dilution on the rising hydrograph. Its relationship to date during the declining hydrograph is more difficult to explain, but could indicate limited seasonal retention through soil adsorption and biological uptake.

There are additional differences among ion concentration trends with date and stream water discharge, however, which could explain some of the multi-year change in ionic concentration. Calcium shows little change in ionic concentration

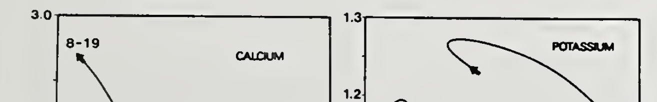

Figure 6.--Time, stream discharge and ionic concentration plots for Ca^{+2}, K^+, NO_3^- and SO_4^{-2} for Lexen Creek in 1986. Ion concentration is plotted against total daily stream discharge with the points joined by increasing date beginning in late April and ending in early October with peak discharge on or about June 10.

over most of the range of increasing stream water discharge. This suggests that Ca^{+2} losses are more a factor of the percentage of annual discharge occurring at high flow rather than total annual flow, total precipitation, or total snowpack moisture or ionic content. Thus, during years of sharp snowpack runoff, as in 1984 and 1986, Ca^{+2} concentration and total discharge would be disproportionately higher than predicted from total annual streamwater discharge.

Nitrate concentrations actually increase with high stream discharge. During peak snowpack runoff biological uptake is still limited. If meltwater is passing through surface soils, it could be picking up mineralized nitrogen along with any contained in the snowpack melt. Again, any natural or man-induced factor which might promote and/or sustain runoff at higher flows would increase both the concentration and output of NO_3^-.

Sulfate also shows little change in ion concentration as the hydrograph increases. Annually its range of concentration change is small. Also, it is the only ion showing a decrease in concentration with decrease in streamwater discharge.

Calcium and SO_4^{-2} are the dominant ions in precipitation and the snowpack, and Ca^{+2} and HCO_3- are the dominant ions in streamwater. Streamwater runoff in 1984 and 1986 was especially high relative to precipitation. This, coupled with only slight change in concentration during the rising and falling hydrograph would account for the significant long-term increase in stream volume-weighted ionic concentration of Ca^{+2} and possibly SO_4^{-2} (figs. 4 and 5).

Except for NO_3^- I found very similar patterns for the main Deadhorse gauging station (Deadhorse Main). These results, along with the findings of others (Bond 1979, Likens et al. 1977), suggest that use of such data comparisons to develop a generalized understanding of the relationship between ionic concentration and stream discharge is effective. However, I have also done such data comparisons for watershed studies in the Upper Great Lakes, and generalizations drawn appear limited to only regional application.

Ion Yields Following Timber Harvest

The assessment of watershed response to vegetation manipulation in subbasins of Deadhorse was confined to those years where complete stream water chemistry exists (tables 3 - 5). Unfortunately, complete chemistry for Deadhorse North prior to and during its treatment does not exist.

Precipitation during and following tree harvest was outside the 95% confidence limits of the pre-treatment period (table 3). The ratio of runoff/precipitation (R/P), plus R/P expressed as a percent of the pre-treatment years, shows a similar response among watersheds except for the increased runoff from the Upper Basin. Precipitation data for the Upper Basin are not available prior to 1982 and confidence limits cannot be calculated for annual R/P, but it appears that inputs were higher in this subbasin. The high Upper Basin runoff probably reflects snow which blows into the basin from the west and is

Table 3.--Mean annual precipitation (ppt) and stream discharge in centimeters prior, during and after treatments for Deadhorse Main, Upper Basin, and North Fork watersheds, and Lexen Creek (control). Values in parentheses are standard deviations. Mean values outside the pre-treatment period 95% CI are underlined.

	Lexen Creek			Deadhorse Main			Deadhorse North			Deadhorse Upper Basin		
	Pre .65,70-71	During 82-84	Post 85-86	Pre .65,70-71	During 82-84	Post 85-86	Pre .65,70-71	During 82-84	Post 85-86	Pre .65,70-71	During 82-84	Post 85-86
Ppt.	82(2)	98	65	68(1.8)	81	54	62(4.2)	74	49	79	105	61
Runoff	53(2.6)	45	54	35(2.2)	36	35	34(2.9)	34	35	51	66	67
Run/ppt	0.65	0.46	0.83	0.51	0.44	0.65	0.55	0.46	0.71	0.65	0.63	1.10
R/P as %	100	71	128	100	86	127	100	84	129	100	97	169

Table 4.--Mean annual concentration (.eq . l^{-1}) of major ions prior, during and after treatments for Deadhorse Main, Upper Basin, and North Fork watersheds, and Lexen Creek (control). Values in parenthesis are standard deviations. Mean values outside the control 95% CI are underlined.

	Lexen Creek			Deadhorse Main			Deadhorse North			Deadhorse Upper Basin		
	Pre .65,70-71	During 82-84	Post 85-86	Pre .65,70-71	During 82-84	Post 85-86	Pre .65,70-71	During 82-84	Post 85-86	Pre 1982	During 1984	Post 85-86
Ca^{+2}	238(25)	469	528	354(62)	747	873		779	884	776(130)	899	909
Mg^{+2}	182(20)	109	142	253(33)	171	214		200	221	177(29)	197	225
K^{+}	16(5)	15	15	20(11)	26	24		24	21	18(7)	24	19
Na^{+}	98(37)	51	62	97(57)	65	70		77	75	58(12)	51	59
NH_4^{+}	----	3.9	1.0	----	0.4	1.3		1.5	1.2	1.8(5.9)	0.7	1.5
NO_3^{-}	0.22(.13)	0.4	0.5	0.50(.25)	0.9	1.6		4.8	4.2	0.4(0.6)	1.8	2.6
SO_4^{-2}	31(10)	39	37	36(12)	49	47		50	49	35(5)	37	38
n	44	38	59	51	40	70		30	70	15	23	71

Table 5.--Annual discharge (eq . ha^{-1}) of major ions prior, during and after treatments for Deadhorse Main, Upper Basin, and North Fork watersheds, and Lexen Creek (control). Values in parentheses are standard deviations. Mean values outside the control 95% CI are underlined.

	Lexen Creek			Deadhorse Main			Deadhorse North			Deadhorse Upper Basin		
	Pre .65,70-71	During 82-84	Post 85-86	Pre .65,70-71	During 82-84	Post 85-86	Pre .65,70-71	During 82-84	Post 85-86	Pre 1982	During 1984	Post 85-86
Ca^{+2}	1261(130)	2110	2851	1239(135)	2833	3056		2649	3094	3958(707)	5933	6090
Mg^{+2}	965(108)	490	767	886(134)	616	749		680	773	903(161)	1300	1508
K^{+}	85(36)	68	81	70(31)	94	84		82	74	92(59)	158	127
Na^{+}	519(245)	230	335	340(228)	234	245		262	262	296(88)	337	395
NH_4^{+}	--	18	5.4	--	1.4	4.6		5.1	4.2	9.2(56)	4.6	10.1
NO_3^{-}	1.2(.6)	1.8	2.7	1.7(.9)	3.2	5.6		16	15	2.0(2.6)	12	17
SO_4^{-2}	164(38)	176	200	126(31)	176	164		170	172	178(30)	244	255
n	44	38	59	51	40	70		39	70	15	23	71

difficult to quantify. During the pre-treatment period, the lower R/P for Deadhorse Main, relative to Lexen, probably reflects the higher evapotranspiration from Deadhorse. Compared to Lexen Creek, the Deadhorse watershed and its subbasins had higher R/P values during disturbance relative to pretreatment R/P values. This was most evident for the Upper Basin. However, the data for Deadhorse Main and Deadhorse North need some qualification since the 1982-84 results follow the disturbance of Deadhorse North by four years. Runoff immediately following disturbance was even higher than reported here (Troendle 1983). Except for the Upper Basin, the disturbed Deadhorse North and Deadhorse Main now appear to have recovered in terms of R/P relative to the undisturbed Lexen watershed.

Similar comparisons of volume weighted streamwater ion concentration (table 4) during this period provide additional evidence as to what factors may be responsible for longer-term trends in streamwater chemistry. Since no stream chemistry data were collected from Deadhorse Main or Deadhorse North during the actual disturbance of Deadhorse North (1977) and there are no pre-treatment chemistry data for Deadhorse North, post-treatment comparisons for Deadhorse North are made with pre-treatment data from Deadhorse Main.

Except for Mg^{+2} and occasionally K^{+}, most ions showed increased concentration during and following the treatment periods. Lexen Creek, the control watershed, had higher concentrations of Ca^{+2} and SO_4^{-2} during and following disturbance in the Deadhorse subbasins (table 4). The possible causes of this have been discussed earlier in relation to the long-term trend of increasing Ca^{+2} and SO_4^{-2} in both Lexen and Deadhorse. Lexen Creek K^{+} concentrations are low relative to the disturbed Deadhorse drainages. Nitrate concentrations increased markedly in the disturbed Deadhorse basins, especially Deadhorse North. The cutting of Deadhorse North began in 1977. Since the 1982-84 concentration data for Deadhorse North actually follow the disturbance of this drainage by four years, the concentration during disturbance was probably higher than observed here. The increase in NO_3^- can be attributed to reduced biological uptake (Knight et al. 1985), increased nitrification (Vitousek et al. 1979), and reduced canopy interception of snowfall resulting in a larger snowpack and quicker runoff (Troendle 1983) which would promote removal of the very soluble NO_3^- from the soil (Vitousek et al. 1979).

Ion yield data (table 5) show the importance of the differing relationships among ion concentration and streamwater discharge discussed earlier (fig. 6). The yield of Ca^{+2} and Mg^{+2} show little evidence of restored ecosystem conservation. The yield of K^{+} from all Deadhorse stations, when compared to Lexen, suggests some but not complete recovery. Yields at Deadhorse Main primarily reflect trends observed in the Upper Basin. The yield of Ca^{+2} and SO_4^{-2} from this basin appears in line with the increased runoff during and following disturbance.

Except for the Upper Basin, there are only limited pretreatment data for NH_4^{+}. Ammonium appears strongly conserved during treatment in this subdrainage, and resumes pretreatment levels after treatment.

Of the ions I analyzed, NO_3^- clearly is the most responsive to disturbance. However, yields vary widely even for the undisturbed Lexen watershed. Again this probably reflects, at least seasonally, precipitation inputs and reduced biological uptake especially in the fall (fig. 2). The only watershed showing some, but minimal, evidence of restored NO_3^- conservation following disturbance is Deadhorse North, but it must be remembered that the data for 1982-84 follow disturbance by four years. The Upper Basin appears to still be losing high amounts of NO_3^- two years following disturbance, and this probably accounts for the trend in yield from Deadhorse Main. Precipitation inputs of NO_3^- were above average in 1984, due mainly to high precipitation amounts. Nitrate loss from the Upper Basin could also be the result of reduced biological uptake, increased nitrification, the increased precipitation runoff, a larger percentage of runoff occurring at high discharge, and the relationship of NO_3^- concentration to stream discharge (fig. 6).

The trends in yield of SO_4^{-2} appear little influenced by disturbance. However, yields from all disturbed watersheds exceed those observed in Lexen. Yield from Deadhorse Main is again influenced by yields from the Upper Basin, which appear to be reflecting differences in precipitation input and higher mean runoff.

Summary

It appears from these preliminary data that the primary factors controlling stream concentrations of ionic species in Fraser watersheds are those related to weathering interacting with natural disturbance in upper basins, precipitation amount and timing (pattern) of snowpack runoff, elevational influences on evapotranspiration, biotic uptake, nitrification, and biomass accumulation of nutrients. Seasonal precipitation inputs of K^{+} and NO_3^-, when concurrent with a decrease in biotic uptake, may be reflected in stream chemistry, but inputs of H^{+} appear to have little or no direct effect on streamwater chemistry.

The long-term trend observed in increasing stream concentrations of Ca^{+2} and SO_4^{-2} appears related more to the pattern of snowpack melt and the amount of runoff passing through soil macropores rather than the annual amount of precipitation or the peak moisture content of the snowpack. However, I have no direct evidence yet to support this hypothesis.

Tree removal has a pronounced effect on increasing watershed NO_3^- loss. This probably is due to reduced biotic uptake and increased nitrification. The loss appears to also be related to any factor, such as slope or aspect, which might increase the snowpack moisture content and its rate of melt.

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The Potential of Subalpine Forest Management Practices on Sediment Production

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Abstract--The potential effect of subalpine forest management practices on sediment production is low when best management practices (BMPs) are implemented. Instream sources are the largest contributor of sediment, while off site erosion is limited due to the physical characteristics of the subalpine environment.

Management of water quality in a forest must consider all activities in watershed forest practices and other nonpoint sources in combination with natural processes (Packer 1967). Soils and geology are the foundation of the forest ecosystem. Soil properties which affect erosion processes in a watershed are of primary consideration.

Soils developing in the subalpine region are influenced by short growing seasons and relatively high amounts of precipitation received as winter snowfall and spring snowmelt. These soils are generally forming in residuum and colluvium derived principally from gneiss, schist, and/or granite and are, therefore, coarse textured. Soils have high infiltration capacities and moderate permeability; thus overland flow is rare. Cryorthents, Cryoboralfs, and Cryochrepts are the predominant great groups found in the subalpine region. Tolerable soil loss for the subalpine environment has been identified as 2-5 tons/acre/year, depending on the specific soil group. Watersheds with erosion rates above this level are identified by the Forest Service as critical (USDA Forest Service 1981).

The sediment load of streams (both suspended and bedload) is determined by such characteristics of the drainage basin as geology, vegetation, precipitation, topography, and land use. The sediment enters the stream system by erosional processes. To achieve stream stability, an equilibrium must be sustained between sediment entering the stream and sediment transported through the channel. A land use activity that significantly changes sediment load can upset this balance and result in physical and biological changes in the stream system (State of Idaho 1987).

The existing form and characteristics of streams have developed in a predictable manner as a result of the water and sediment load from upstream. Natural channels are self formed and self maintained. Both water and sediment yields may change due to silvicultural or other land use activities upstream. Increases in water and sediment yields should be evaluated in terms of potential effects on channel stability.

Sediment routing and storage are particularly important components in the transport process of sediment loads through the stream system. They are critical to the quantification of short and long term impacts of land use activities on stream channels and beneficial uses. However, the storage and routing processes are highly variable and exhibit non steady state behavior. Continuously evolving relationships involving sediment supply and energy availability are used to estimate sediment discharge changes as the result of land use activity.

Maintenance of stream sediment transport (and minimizing vegetation growth within the channel) should retain the channel's capability for passing floodflow discharges. This physical concept is used to determine channel maintenance flows that will maintain stream channel stability for the orderly conveyance of water from and through the National Forests (USDA 1985).

Results from studies in subalpine watersheds have identified correlations between annual peak discharge and annual sediment discharge. A similar relationship between total annual flow and annual sediment discharge has also been determined. A major portion of the sediment load is composed of bed material derived from streambank erosion and channel degradation (Stednick, unpublished data, among others). Substantial increase in runoff may upset channel stability, increasing turbidity and sediment concentrations.

Forest practices have the potential to affect water quality in a number of ways (Sopper 1975). Accelerated sedimentation has been identified as the primary water quality problem related to forest management in the western United States. Activities associated with timber harvest, yarding, and road construction and maintenance result in disturbance of soils and vegetation and may increase soil susceptibility to erosion. These disturbances may alter the hydrologic cycle, generating

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more overland flow for detachment and transport of sediment. Forest harvesting has been moving towards progressively steeper sloped lands in recent years, intensifying the problem (King and Gonsior 1980).

Roads

Roads are the primary source of sediment from forested watersheds. It is estimated that 90% of the sediment production from timber harvest can be attributed to roads (Megahan 1972). Sediment yield increases of two to three orders of magnitude over undisturbed sites have been observed (Megahan and Kidd 1971). The magnitude of sediment contributions from roads vary greatly, depending on the soil type, geology, topography and climate characterizing the particular site and road construction practices. Roads on gentle to moderate slopes and stable topography have a low potential for contributing sediment when properly constructed and maintained. However, roads located adjacent to streams, on steep slopes, and/or unstable topography have a high potential to produce sediment for a long period of time if not properly planned, constructed, and maintained.

Sources of sediment from forest roads are (1) direct movement of soil during construction and maintenance, (2) surface erosion, and (3) mass erosion (Youngberg, et al. 1973, Larse 1970, Fredriksen 1970, Fredriksen 1965). If the road is located so that construction activities cause direct movement of soil into stream channels, then it is likely that future maintenance activities will also contribute sediment, especially if the road encroaches directly upon the stream or riparian zone.

Climate, vegetative cover, slope, and soil characteristics are important in determining sediment yields from undisturbed sites. Road construction alters the latter three and generally increases erosion and transport of sediment for some time (Megahan 1975). Removal of vegetation and the litter layer from soil surfaces exposes soil particles to the energy of raindrop impact, the primary agent of interrill erosion (Meyer, et al. 1975). The reduction in infiltration necessary for stability increases road surface runoff, which may be augmented by overland and subsurface flow from the cutslope and drainage area above it. As flow and the energy associated with it accumulate and become concentrated in channels, rill and gully erosion cause much larger volumes of sediment to be detached and transported. Properly designed roads will minimize concentrations of flow through outsloping and frequent water diversions.

Surface erosion is greatly accelerated during and shortly after road construction. Approximately 84 percent of the total sediment production for a 6 year period was produced during the first year after road construction (Megahan 1972). Once the exposed soil revegetates or becomes armored, surface erosion declines rapidly. Concurrent erosion control during construction with immediate stabilization of exposed soils are needed to minimize surface erosion and sediment contributions.

Two other features of road construction are not found on every segment but may be important in determining the distance of sediment movement. When the road is pioneered, cut timber is temporarily stored adjacent to the road, usually on the downhill (fillslope) side, and occasionally a dip may coincide with one of these log decks, diverting sediment laden water between the logs. The log decks may then act as baffles to reduce flow energy and increase deposition during the period immediately after road construction when sediment movement is greatest.

The stumps from these right of way trees may be disposed of either by burning or by burial. Generally burial is used because it is quicker and easier, occasionally leaving a large area of bare disturbed soil immediately downslope from the road. If high energy runoff is diverted over these burial pits, rill and gully erosion may result. Good management requires burial pits to be discrete relative to the road. Both log decks and burial pits occur infrequently relative to the number of water diversions along the road.

Surface erosion results from raindrop impact on exposed soils and sheet, rill, and gully erosion of unprotected cuts and fills. It is influenced by rainfall/snowmelt characteristics, soil characteristics, topography, and plant and litter cover. The reported magnitude of sediment contributions from roads varies greatly (Campbell 1983, King 1979, Beschta 1978, Krammes and Burns 1973, Brown and Krygier 1971, among others). An evaluation of sediment contributions from surface erosion on jammer roads in the Idaho batholith revealed a 1560 fold increase in sediment production during the year following construction, and a 50 fold increase 3 years later. Approximately 30 percent of the total road erosion was due to surface erosion and 70 percent to mass erosion (Megahan and Kidd 1972).

Sedimentation processes occur on all of the features of a typical road segment (Haupt 1959, Haupt and Finn 1963, Bethlahmy 1965, Bethlahmy 1967, Dyrness 1967, Falletti 1977). The cutslope is a steep bank on the uphill side of the road which consists of relatively stable material which was in place before the site was disturbed. Erosion may occur here if overland flow spills down the cutslope or if subsurface flow emerges from the bank.

The road surface is a bench of highly compacted material where most of the overland flow is generated. This surface is slightly outsloped in order to direct sheet flow to the outer edge of the road, where it can be diverted before concentration of flow occurs. At intervals, dips in the road are placed in order to divert any runoff which may be flowing along the axis of the road. The distance between these dips, or road segment length, determines the total area which may contribute to one of these water diversions.

Road derived sediment reaching the stream course has been shown to decrease exponentially with time since road construction (Megahan and Kidd 1972, King 1979, King and Gonsior 1980). Significantly accelerated surface erosion was observed only during a few thunderstorms immediately following road construction. Re establishment of vegetation is an

obvious factor influencing stabilization but physical processes such as development of pavement and armoring may be involved as well. More easily eroded fine particles are readily transported, and surface erosion decreases as their availability is diminished.

As sediment laden runoff reaches the edge of the roadfill, it is dammed by debris and energy is dissipated by litter and vegetative cover. Windrowing of slash along the toe of fillslopes may aid in controlling erosion and subsequent sedimentation (Cook and King 1983). This reduces the energy available for transport, causing deposition which decreases the distance sediment will be moved. However, the actual processes which describe and the parameters that control the delivery of eroded material downslope are less well understood than those for erosion, and data for sediment delivery are scarce (Campbell 1983, USDA Forest Service 1980). In the discussion of sediment delivery in Water Resources Evaluation of Nonpoint Silvicultural Sources (WRENS), a sediment delivery index is presented with the acknowledgement that data to support the index does not exist, and more research is necessary to establish reliable estimates of sediment delivery (USDA Forest Service 1980). Equations that utilize erodibility indices based on rainfall intensity may be grossly in error when applied to the subalpine environment, since much of the streamflow is from snowmelt (Leaf 1966).

Studies in Idaho indicated that on well designed roads most sediment flows travel less than ten meters from the toe of the fillslope and occur soon after construction (Haupt and Kidd 1965). Buffer strips of ten meters were recommended to capture all of the sediment being transported from the road disturbances. Sediment movements of more than twenty meters have been observed on the Fool Creek drainage of the Fraser Experimental Forest (Troendle 1981).

The problem of road erosion is also related to the density of the road network. Careful planning can help minimize road density. An unplanned road system constructed by the logger at the Fernow Experimental Forest in Colorado occupied 4.8 to 7.0 percent of the area, while a well planned road system on similar topography only occupied 2.5 to 4.6 percent (Mitchell and Trimble 1959). In addition to careful planning, the harvesting system employed largely governs the required road density. Jammer logging may expose 25 to 30 percent of the area as roads while longer cable systems such as a skyline setup may only expose 2 percent of the area (Rice, et al. 1972).

Mass wasting related to roads includes fill and backslope failures, slumps, earthflows, landslides, mudslides, and rockslides (Swanston 1981, Swanston 1976). Surface and mass erosion from roads are related to one or more of the following: removal of protective cover, destruction of soil structure, increases in slope gradients, decreases in infiltration capacities, interception of subsurface flow, decreases in shear strength, increases in shear stress, and concentration of generated and intercepted surface water, and reduced rooting strength (Gray and Megahan 1981, Megahan 1977, Swanston 1970).

It is generally thought that decay of tree roots and the resulting reduction in a soil's shear strength contribute to mass soil movement on high hazard sites (Burroughs and Thomas 1977, Davis 1976). Control of this hazard relates to recognition of the failure potential of an area and regulation of both the yarding system and silvicultural prescription (Brown, et al. 1976, Rothwell 1971).

Steep slopes, relatively shallow soil, and rapid, large volumes of water are generally required for mass wasting to occur (Megahan 1975). However in some situations, prolonged snowmelt and low intensity rainfall events can also contribute to mass wasting. Careful route selection is required to avoid potential problem areas. Mass erosion is not significant in the subalpine environment.

Work in the Idaho batholith led to the conclusion that road design parameters may be important in predicting erosion, but downslope transport of the material was primarily controlled by slope steepness and the type and amount of cover.

Other investigators (Haupt and Kidd 1965) have reported similar trends after measuring sediment movement downslope from cross ditches and in ephemeral channels. While there was much variability between sites, movement downslope had effectively ceased three years after roads had been put to bed, i.e., closed to traffic, water barred, culverts and bridges removed, and allowed to revegetate.

Earlier studies of sediment transport along Fool Creek (Leaf 1966, Leaf 1974) indicated little or no water quality degradation is to be expected from road construction with proper planning, construction and maintenance. A model was fitted to the Fool Creek Watershed based on sediment yield data collected by an in stream sediment trap. This model predicted decreased sediment yield with time, as a function of topographic and road engineering characteristics (Leaf 1974). It did not address the hillslope processes which are involved in determining sediment delivery to the stream.

A set of guidelines for road sediment control were developed for the Northern Rocky Mountain region (Packer and Christiansen 1964) and for roads in Idaho (Megahan 1977). Factors affecting the distance sediment moves downslope were identified as cross drain spacing (road segment length), kinds and spacing of obstructions, cover density, soil particle size distribution, and road age.

Much of the data describing the decrease in sediment yield with time has been collected on roads that were put to bed. In these cases, a dynamic equilibrium evolves from channel stabilization and erosion pavement development. However, roads receiving continuous use may not recover, or response may be much slower, as a result of continued disturbance. This effect has been demonstrated simply by limiting vehicle traffic in areas of the Deadhorse and Fool Creek watersheds in the Fraser Experimental Forest (Troendle 1983).

Sediment contributions from forest roads can be minimized through proper planning route selection, design specifications, construction practices, maintenance and stabilization measures (USEPA 1975). To maintain water quality,

greater attention is being given to soil and geologic characteristics, avoidance of high hazard areas, improved engineering surveys, improved road design and improved construction methods (Clayton 1983, Gardner 1979, Stone 1973). Proper location of roads relative to streams is also essential. However, a strong preventive approach is not always free of failure, and supplemental corrective measures may be required to minimize sedimentation from roads (U.S. EPA 1975).

Standards and guidelines used by the Forest Service include establishment of 30-meter (100-foot) buffer strips along all water courses (USDA Forest Service 1981). Road construction should be scheduled during dry periods with low flow and maintenance activities should be scheduled to avoid prolonged wet periods. Riparian strips have standards and guidelines for basal area reduction, surface disturbance and slash disposal practices (USDA Forest Service 1981).

Harvesting

Timber harvesting and subsequent yarding can increase sediment in streams by increasing surface erosion rates and increasing the risk of mass soil movement (Brown, et al. 1976, Davis 1976). Site disturbance can reduce infiltration rates, and hence, the quantity of overland runoff and related surface erosion.

Methods used for the movement of logs from the stump to a landing can be classified as tractor, cable, aerial or animal. Both aerial and animal yarding are almost nonexistent in the subalpine environment. Tractor skidding is accomplished with either crawler or wheel type units, both of which are frequently equipped with arches for reducing the extent of contact between log and ground.

Site disturbance will vary greatly with the type of skidding or yarding system. Crawler tractors generally cause the greatest amount of site disturbance, followed closely by wheeled skidders, but on some sites use of wheeled skidders can result in more compaction than use of crawler tractors (Davis 1976, Bell, et al. 1974). One method of decreasing the amount of soil disturbed by crawler tractors or wheeled skidders is through careful layout of skid trails (Rothwell 1971). Planning for skidroad location and number can greatly decrease the impact of tractor logging. Cable logging systems will result in less site disturbance, because yarding trails are established to the yarding tower machinery restricted to road surfaces. Cable systems can be ranked in order of decreasing soil disturbance as follows: single drum jammer, high lead cable, skyline, and balloon (Brown, et al. 1976, Davis 1976, Stone 1973). Helicopters and balloons will likely result in minimum site disturbance, but both are costly and subject to operational constraints.

Sediment yields from Fool Creek after logging were relatively large during the years immediately after treatment. Yields in subsequent years were considerably less and not significantly different from the pretreatment means (Leaf 1966). The return of suspended sediment concentrations to pretreatment levels has been best modeled as a negative exponential (Leaf 1974, Megahan, 1980). This time factor should and can be considered in land use planning and design of best management practices.

One of the best methods of controlling the entry of sediment into streams from harvesting on roads is through the use of buffer strips (USEPA 1977, Brown, et al. 1976, USEPA 1975, Bell 1974). Buffer strips have also been shown to be effective in reducing the entry of logging debris into streams and in controlling stream temperature.

The silvicultural prescription implemented by harvesting can influence both water quantity and water quality. Silvicultural prescriptions for the subalpine may include shelterwood, seed tree, clear cutting, and selection (U.S. EPA 1976). Prescription of a particular system will depend upon existing conditions and land management objectives.

Conclusions

Subalpine forest management practices include roading and silvicultural treatments that involve tree harvesting. These practices have been evaluated for nonpoint source water quality impacts. Much of the literature on forest management activities and water quality changes is from the Pacific Northwest and has documented dramatic water quality changes (or impacts). The identified processes are applicable to the subalpine forest, but the observed water quality changes are not. The potential of subalpine forest management practices on sediment production BMPs are implemented is low. Sediment generation may occur from roading and harvesting, however the increase is short lived and often not measurable when best management practices have been utilized. The major portion of the sediment load is derived from in stream sources, i.e., streambank erosion and channel degradation. Suspended sediment concentrations are low in undisturbed subalpine watersheds. Management activities may increase these concentrations for brief time periods, however suspended sediment concentrations and turbidity changes can still meet state water quality standards.

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Watershed Research for Management Needs: Which Way We Ought to Walk from Here

Rhey Solomon[1]

The Fraser Experimental Forest was established in 1937 to study natural plant communities and determine their effects on snow accumulation and water yield changes in response to management of the subalpine forests. The work derived from this experimental forest has served well in providing managers with watershed relationships that help them understand water yield and snowpack processes (Alexander et al. 1985).

However, before we roundly endorse research from Fraser and other experimental forests, let us step back a little and take a more introspective look at where we have been and how we have approached research and the management application of research for the subalpine forest.

I'm going to be a little self-criticizing, only because I feel self analysis is always helpful in keeping on the right track. In this effort, I'll rely on a quote from Alice in Wonderland where Alice is confronted on her walk by the Cheshire cat. Alice, not really knowing where she was or where to go, asked the cat, "Would you tell me, please, which way I ought to walk from here?" The Cat answered with, "That depends a good deal on where you want to go." Alice thought for a while and responded, "I don't much care where." The cat in his wisdom said, "Then, it doesn't matter which way you walk." Alice, being a little concerned, states, "So long as I get somewhere." As a final reply the cat matter-of-factly says, "Oh you're sure to do that if you only walk long enough."

I use this passage from Alice in Wonderland because I feel it parallels, in many respects, the questioning and answering that goes on between National Forest System managers and Research. Management often ask of Research which way it ought to walk. Research properly asks management just where it wants to go. The question to evaluate in today's talk is whether Management has adequately given Research the desired destination (Objectives) or, as like Alice, didn't much care. In the end, as the cat points out, "You're sure to get somewhere if you only walk long enough." Has Research taken Management where it wanted to go, or have we gone down a path getting to some destination but not sure if it's where we wanted to be?

Let's evaluate how well we did in our journey -- did we take a path not really caring where we got to -- or did we more deliberately choose where we wanted to go? I'll start first by expressing an overriding objective or destination for National Forest System management derived from enabling legislation, the Organic Act, which designates the purposes of the National Forests:

> ...For the purpose of securing favorable conditions of water flow, and to furnish a continuous supply of timber....

We often lose sight of this objective, especially when framing questions for Research. We focus on very technical questions. We therefore have to ask ourselves, can we better define and manage for "favorable conditions of flow" today than we could before undertaking research at Fraser and the other experimental watersheds? This is the central theme of my talk today -- do we better understand our basic watershed objective in today's world of simulation models, computer tools, and mapping techniques than we did 50 years ago?

We can start first by looking at how we in the National Forest System have chosen, through our actions and policies, to define "favorable conditions of flow." Typically, favorable conditions of flow have been translated into three component parts, (1) water quality, (2) water quantity, and (3) water timing. Generally, these aspects of favorable conditions of flow have been related to conditions of the land. We have developed a term over the years that has come to encompass all three measures of water as well as land conditions -- this term is "watershed condition."

Using this watershed condition theme, the management issues emerging in the 1930s and 40s were related to off-forest impacts -- flooding, lack of water, debris clogging of irrigation works, and maintaining navigability of streams. How well did research, and more specifically work at Fraser, respond to these issues? The watershed work done at Fraser was primarily aimed at questions dealing with water yield and specifically snowpack management to increase yields and affect runoff timing. Table 1 shows the published watershed research from the Fraser Experimental Forest over the last five decades (Alexander et al. 1985).

As shown in table 1, the work at Fraser was aimed at answering management questions about water yield response. Over the first three decades this research appeared to be steady. However, in the late 70s and on into the 80s this

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Table 1.--Published watershed research from the Fraser Experimental Forest.

	Decade					
	40s	50s	60s	70s	80s	Total
Water Yield	17	20	21	18	8	84
Sediment/Erosion	--	--	2	7	--	9
Measurement	11	2	5	8	--	26

research declined and culminated in a series of papers that, generally, satisfied questions about the water yield issue in the west (Hibbert et al. 1974, Clary et al. 1974, Brown et al. 1974, Leaf 1975). Of note, is the work done at Fraser on measurement and monitoring in the 40s and to a lesser extent in the 50s, 60s, and 70s. Some of the techniques of water measurement developed at Fraser have been used as the basis for some of today's measurement and monitoring approaches (Wilm 1943, Goodell 1951, Leaf and Kovner 1970, Leaf and Kovner 1971).

Work from Fraser has demonstrated that cutting patterns affect streamflow in both quantity and timing of delivery. The work over the last 50 years has led to some of the most applied research emanating from experimental forests. The initial studies focused on hydrologic processes that affect water response (Bertle and Dunford 1950, Goodell 1948, Hoover 1962, Hoover and Leaf 1967). All of this process research on water yield and timing culminated in hydrologic computer models that synthesized work at Fraser (Leaf and Brink 1973, Leaf and Brink 1975). These models have enabled managers to easily ask "what if" questions and be provided answers -- a most valuable tool for management application of research results. A final extension of the work done at Fraser was made by Troendle and Leaf in Chapter III, Hydrology of the WRENSS Handbook (USDA Forest Service 1980). This procedural handbook has served as a principal tool for hydrologic analysis in Forest Planning and in design of best management practices for control of nonpoint pollution.

Of concern, however, is that watershed research derived from Fraser has been declining over the last decade. This is, perhaps, in part due to a shift in multiresource research, but also due to a deemphasis on watershed research. A question then arises, has Fraser fulfilled its watershed research purposes and few opportunities exist, or have we not refocused research on Fraser to today's watershed condition issues?

Let's now come back to our general charge of maintaining favorable conditions of flow. Has research helped to better define favorable conditions of flow and watershed condition, or have we been, like Alice, wandering down a path to get somewhere not sure where we have gotten? I think it can be said that the issues of the 30s, 40s, and 50s dealing with flood flows and water yield have been adequately addressed by research. The research done at Fraser and elsewhere has helped management better understand the processes affecting these components of watershed condition, and this research has been translated into better on-the-ground watershed management. Unlike Alice, we did care where we were going and took a deliberate path. However, we may be at a fork in the road, and again need to ask "which way we ought to walk from here."

Future Watershed Research Opportunities and Challenges

With the environmental awareness of the 1970s and the increasing populations in the West, came water quality legislation and demands for water uses that form the watershed issues of the 80s and 90s. The watershed issues of the future focus around (1) instream water uses and needs and their conflict with demands for water diversions, and (2) improving or maintaining water quality while meeting increasing resource demands of the land. Issues such as minimum stream flows for fisheries, instream flows for wilderness and riparian communities, flushing flows, and channel maintenance flows form the water yield and timing research needs for the coming decades. Approaches to control and management of nonpoint sources of pollution including monitoring techniques, water quality standards, and BMP design form the water quality research needs.

Research results on water yield and snowpack dynamics appear sufficient to answer management needs, and the marginal benefits to be gained from continuing this research do not warrant the investment, especially given the critical needs in the other areas of water quality and instream flows.

Water Quality Research Needs

If the current reliance on BMPs as the mechanism to control nonpoint pollution is to be successful, research information has to underpin this strategy. But before focusing on these research needs, let me first state the strategy -- or for Alice's sake, identify the destination. The key to nonpoint pollution control is through application of preventative practices (BMPs) rather than a strict reliance on instream numeric water quality standards.

The Forest Service has developed a management strategy that is compatible with the Clean Water Act and resolves the dilemma of using numeric water quality criteria as a performance standard. The primary strategy for control of nonpoint sources should be based upon design and implementation of preventive practices determined necessary for the protection of identified uses. Surveillance should be based on ensuring implementation of acceptable best management practices. The objective of BMP design should be that their implementation is the most practical means of attaining water quality goals. Water quality goals include water quality standards that adequately reflect the needs of identified beneficial uses.

It is important that implementation of land management practices developed to meet water quality objectives, and agreed to by regulatory agencies and land managers as "Best Management Practices," be sufficient to meet legal responsibilities of land managers. In an appropriate BMP/water qual-

ity standard relationship, the standards serve as a basis for measuring accomplishment of protection to the "extent feasible" and "maximum extent practicable." It is inappropriate for nonattainment of a water quality standard to be grounds for enforcement action where the agreed on BMPs were implemented. Nonattainment should be grounds for reassessing the effectiveness of BMPs and nonpoint source programs in meeting water quality goals. Monitoring results should be used for improving practices where a higher level of protection is feasible, and/or modifying water quality standards when standards are found to be unrealistic. Water quality standards are not replaced by BMPs in this strategy. Water quality standards serve as a means of evaluating program success and determining needs for change in this program, rather than in direct program enforcement. If we use the concept presented here of BMP design, monitoring, feedback of information, and adjustment of BMPs and/or water quality standards, we can and should expect that specified BMPs will meet water quality standards with time.

The strategy as presented does not presume that all responsibility for protection of the environment is automatically taken care of by compliance with designated BMPs. If environmental harm is found following application, then mitigation measures must be considered and their application negotiated. The important point is that application of agreed-to practices constitutes compliance with requirements of the Clean Water Act.

The Forest Service nonpoint source management system consists of: (1) design of site-specific BMPs based on technical, economic, and institutional feasibility, (2) application of BMPs based on scheduling, intensity, placement, and maintenance, (3) monitoring to ensure that practices are correctly designed and applied, (4) monitoring to determine effectiveness of practices in meeting water quality objectives, the appropriateness of water quality criteria for describing the needs of water dependent resources, and (5) a mechanism to adjust BMPs and/or standards as appropriate.

Research has an important role in underpinning this strategy by (1) providing information for the design and implementation requirements of BMPs, (2) providing monitoring techniques and designs that are cost-effective yet provide meaningful results, and (3) developing water quality standards that better tie to the beneficial uses and do not have the stochastic variability of water quality criteria currently being used.

Water quality standards as used in this discussion need to be defined in order to clarify the concepts presented here. Water quality standards are made up of an identification of beneficial uses, an identification of water quality criteria necessary to support those uses, and an antidegradation policy statement on how water is going to be maintained or improved. It is important to consider problems and needs as related to the three component parts of water quality standards. When reviewing existing State water quality standards, it becomes readily apparent that many criteria do not adequately represent the needs of beneficial uses. Existing water quality standards were primarily developed during the early to mid 1960's to address point sources of pollution,and tend to be discrete values. To adequately reflect the variability of the natural system, water quality standards need to be adjusted to include a stochastic expression.

The relationship between many beneficial uses and water quality criteria is not well understood, particularly in light of the natural variability discussed above. Directly related to this is a lack of understanding of the relationship between land management practices and water quality impacts. Until land use practices are better linked with water quality responses, it is difficult to define a water quality standard that is truly meaningful in nonpoint source control.

The concept of antidegradation causes concern because there are numerous ideas as to what is meant by the term. The term is not found in the Clean Water Act,but has its origin through EPA interpretation of the goals as stated in the Act. Some interpret antidegradation to mean no change at any point at any time. Such an interpretation would preclude any and all land management activities. A more reasonable interpretation would include both a temporal and spatial component. In my view, this is the only way in which natural resources can be managed in a multiple use context.

Time and space considerations of antidegradation raise another concern facing the Forest Service. How can the concern for cumulative effect be dealt with in both a planning context, and in measurement or monitoring? Forest planning and environmental analysis associated with planning and project design must consider cumulative impacts. Research and technical development of evaluation techniques are needed to discharge agency responsibilities.

Research can also help develop the water quality models that will undoubtedly be needed for the proper design of BMPs and projecting BMP effectiveness.

Instream Flow Research Needs.

Determining the instream flows necessary to support water-dependent resources is critical to many land management decisions. Management needs such information during water rights adjudications and in establishing special use permit conditions. A method has been developed for estimating the amount of flow in quantity and timing necessary to maintain channel conditions. Unfortunately, this has been developed for only one physiographic region. In addition to the need for expanding this method to other areas, there is no method for determining the amount of water needed for recreational use, esthetics, and wilderness. This will be a critical need in the very near future, particularly in the Western States where water is in short supply. These are not easy questions. If water is needed in a babbling brook or a water fall, how much is needed? If water is needed to maintain the wilderness character, how much is needed? If some water can be removed, how can an estimate be made? It is important that rational methods

which are technically defensible be developed for these flow determinations.

In most cases, courts have not ruled against agency decisions if those decisions were arrived at using procedures and methods that produce consistent results. A problems arises when decisions are shown to be arbitrary and capricious. The best defense is to have defensible methods upon which to base decisions and to clearly display these efforts to the public. Whether we like it or not as resource managers, we operate in a glass house and must justify our actions.

Hydrologic Models And Research Needs

For the forest land manager, existence and use of models have been both a benefit and a curse. As a benefit, models have provided valuable insight for making land management decisions. As a curse, models have been used inappropriately by regulators who choose not to recognize model limitations in land use control decisions. A problem lies in how models and model use are viewed by the specialist or researcher, and how they are viewed by a regulator. Models as used in research are generally constructed to better understand how a "system" operates. Cause-effect relationships are established between land use activities and hydrologic parameters to match the natural system. The match is established through repeated refinement of parameters and interrelationships among parameters based on runs of known data sets. Once a good correlation is established between what actually occurs as based on the data set and model prediction, then parameters can be varied and results evaluated based on model output. This process allows for study of the "system;" hopefully, providing insight into how natural processes work. Even in this use of models, it is dangerous to place too much reliance on absolute values obtained. How well models approximate the real world is dependent on our interpretation of cause-effect relationships: the more empirical the relationships used the more questionable the results.

Thus far in this discussion of model use, no attempt has been made to apply the model to a situation outside data sets. When models are applied outside data sets, reliance on generated information must be viewed carefully. Specialists have often used model extrapolation to make estimates of the impact for proposed land management practices. Such results cannot be used as absolutes, however, and must be used as indicators only so that informed decisions can be made based upon risk. Unfortunately, in some cases in our attempts to get "the job done," specialists and line officers have used model outputs as accurate representations of reality, rather than as only one piece of information with appropriate recognition of limitations. In some cases, for example, we have displayed comparisons between management alternatives based on model estimates that indicate small differences, when in fact the differences between alternatives are much less than the statistical reliability of the models.

In quests for a means to estimate effects of land uses in advance of activities, regulators have often used, or proposed to use, models to estimate impacts and to control land use. While it would be desirable to predict such impacts in advance, it is not possible to do so at a level of accuracy and precision sufficient for regulatory control.

It is important for research to continue development of better and more accurate cause-effect models and to accommodate stochastic inputs for evaluation of risk based on climatic variability. It is incumbent on the technical community to ensure that models are not misused by land managers and regulatory agencies. Using a model just because it is the "best we have" is not good enough. If it does not answer the questions posed it should not be used.

The Fraser Experimental Forest can contribute to investigation of both the instream needs as well as the water quality needs.

Conclusions

Research has provided useful information to help management better understand what has come to be broadly defined as watershed condition. However, the research questions asked today are far more complex than in the past. To answer these questions, research can no longer rely on an individual scientist or singe experimental forest. Integrated research must be employed. This integration will involve a team approach using hydrologists, soil scientists, geologists, fisheries biologists, foresters, and other disciplines. This research will also necessitate integration of research results from many experimental watersheds. The Fraser Experimental Forest can contribute to investigation of both the instream needs as well as the water quality needs.

I challenge research to undertake these research opportunities discussed today in ways much different from the past. The use of team research may be somewhat new for many scientists, but it is a necessity if we are to gain answers to the complex issues of today. I also challenge research to keep a focus on the overall objective, "favorable conditions of flow," as research projects are contemplated. Each watershed research project should fit within this overall objective.

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2HS

Big Game Habitat Research in Subalpine Forests in the Central Rocky Mountains

Glenn L. Crouch[1]

Abstract.--Research findings indicate that subalpine forests similar to those on the Fraser Experimental Forest provide growing season habitat for deer and elk, but are unsuitable as winter range because of deep snow. Even in the growing season, their value as forage producers may be limited by closed canopies. Segments of these forests apparently can also provide year-round habitat for moose.

The Fraser Experimental Forest is a high elevation (8,800 to 12,800 feet), north-facing alpine and subalpine tract of about 23,000 acres in north-central Colorado. About one-third of the total acreage is above timberline and the remainder is tightly forested, with few natural openings (Alexander et al. 1985). This paper is concerned with the subalpine portion of the Experimental Forest.

Rocky Mountain elk *(Cervus elaphus nelsoni)* and mule deer *(Odocoileus hemionus hemionus)* are the major big game species that seasonally utilize the alpine and subalpine communities on the Fraser Forest. The Forest serves as summer range for nominal, but huntable, populations of elk and deer (fig. 1). Both are absent when deep snow hinders their movement and covers the low-growing understory vegetation that is virtually the only nonconifer food source available in winter. The wintering areas of Fraser elk and deer have not been identified, but probably are north and west of the Experimental Forest on the eastern edge of the well-known Middle Park winter range (Gilbert et al. 1970, Carpenter et al. 1979; Tiedeman et al. 1987) (fig. 2).

Black bear *(Ursus americanus)* are occasional visitors, and moose *(Alces alces shirasi)* may have become resident on the Forest since their reintroduction into Colorado in 1978 and 1979 (Nowlin 1985).[2]

The newest big game animal on Fraser also is the largest. In 1978, moose were released into Colorado, near the town of Rand, about 40 miles north of the Experimental Forest (Nowlin 1985). During their first year, at least one moose traveled almost half the distance from the release site to the Fraser Forest. By 1982, moose were infrequently observed on the Forest, and soon afterward a year-round population apparently was established. These moose move extensively through the year, but their major habitat appears to be willow-dominated areas adjacent to the lower reaches of the larger streams on, and adjacent to, the Experimental Forest (fig. 3). Although numbers of moose are not known, they are regularly seen by workers on Fraser.

VEGETATION

Vegetation on the Forest has not been classified or mapped, but the *Abies lasiocarpa/Vaccinium scoparium* habitat type is dominant, and *V. scoparium* is the major understory species below timberline (Wallmo et al. 1972, Crouch 1985, Hess and Alexander 1986).

Other habitat types present in the *A. lasiocarpa* series include *A. lasiocarpa/Senecio triangularis* and *A. lasiocarpa/Calamagrostis canadensis.* Both produce much understory vegetation, but are limited to moist sites and occur sparingly on most of the Forest. *A. lasiocarpa/Carex geyeri* is present; but its acreage also appears to be limited.

Additional habitat types or plant communities identified include *Pinus contorta/V. scoparium, P. contorta/Shepherdia canadensis,* and *P. contorta/Carex geyeri.* Acreages of these are relatively small.

Infrequent, but potentially important, communities include a few unclassified, nearly pure stands of *Populus tremuloides,* mid-height *Salix* spp.-dominated communities along water courses, a single stand of *Artemisia* sp., and minor acreages of multispecies grass-forb stringer meadows. Also present, at lower elevations that burned during logging early in the century, is a 900-acre *P. contorta*-dominated stand that contains various proportions of *P. tremuloides.*

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[2]Personal communication, Colorado Division of Wildlife, April 1987.

BIG GAME HABITAT RESEARCH

With few exceptions, habitat studies have been evaluations of the experimental application of various timber management practices that are designed to enhance water production for downstream users.

Completed Studies

Fool Creek

Research on big game habitat on the Experimental Forest began in the late 1950s after timber was harvested on the Fool Creek study area (figs. 4 and 5). There, during 1954-56, 278 acres of mature timber on 550 acres of commercial forest land were clearcut in alternate, variable width strips, to increase streamflow (Alexander et al. 1985). Two years after logging, more mule deer fecal groups were found on clearcut than on uncut strips, and production of some plant species was somewhat greater on the clearcut areas (Porter 1959). Fecal counts in 1966, about 10 years later, showed nearly three times more deer droppings per acre on clearcut than on uncut strips (Wallmo 1969).

Figure 1.--Elk in an aspen opening in central Colorado.

Figure 2.--Middle Park; probable winter range for deer and elk from the Fraser Experimental Forest.

Figure 3.--Moose tracks in winter on the Fraser Experimental Forest.

Deer feeding preferences and amounts of forage available to them in the snow-free season were studied in 1970 and 1975, 15 to 20 years after logging. Results showed that deer fecal counts and forage production were still greater on clearcut than on uncut strips, but that inherent forage quality as indexed by crude protein content and digestibility was not different between the two treatments (Wallmo et al. 1972, Regelin et al. 1974, Regelin and Wallmo 1978).

Deadhorse Creek

Crouch (1985) monitored vegetation response to a different timber harvest pattern. This study, conducted on a south-facing segment of the 667-acre Deadhorse Creek watershed, involved a state-of-the-art cutting practice for maximizing water production (fig. 6). Here, 12 more or less evenly spaced, 3-acre circular patches were clearcut in a 101-acre segment of the watershed (Troendle 1983). The Deadhorse site was similar to that on the Fool Creek study area, but

understories generally were drier and less productive (Wallmo et al. 1972, Crouch 1985).

Data were collected over 5 years in five of the twelve 3-acre plots to be clearcut, and five uncut controls (figs. 7 and 8). All of the control and four of the blocks to be clearcut were *A. lasiocarpa/V. scoparium* habitat types. The remaining harvest block was a much more mesic *A. lasiocarpa/Senecio triangularis* habitat type. By the fifth growing season, plant production was unchanged on the uncut blocks; but had increased from 225 to 673 pounds per acre on the average blocks, and from 622 to 3,295 pounds per acre on the moist block (fig. 9).

Crude protein content was unchanged on uncut plots, but increased on the average clearcuts after logging.

Over the 5-year evaluation, there were no differences in numbers of elk fecal groups before and after clearcutting, although numbers increased gradually on the average clearcut sites. Numbers of deer droppings, however, increased over the postlogging period on all blocks. Elk and deer droppings were both more abundant after clearcutting on the mesic site.

The major response of understory production and herbivore activity on the mesic *A. lasiocarpa/Senecio triangularis*

Figure 5.--Fool Creek watershed in 1985.

Figure 4.--Fool Creek watershed in 1957.

Figure 6.--Three-acre circular clearcuts designed to augment streamflow on the Deadhorse Creek watershed.

Figure 7.--Clearcut block in subalpine timber 2 years after logging on the Deadhorse Creek watershed.

Figure 8.--Clearcut block shown in figure 7 in the ninth winter after logging.

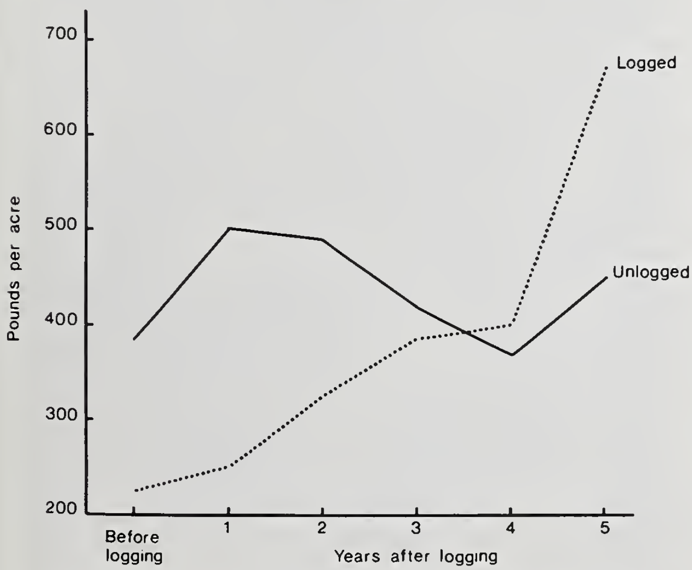

Figure 9.--Dry weight understory plant production (pounds per acre) on uncut and clearcut blocks, Deadhorse Creek watershed.

Figure 10.--Growing stock level (GSL) 40, 8 years after thinning in Pinus contorta, Fraser Experimental Forest.

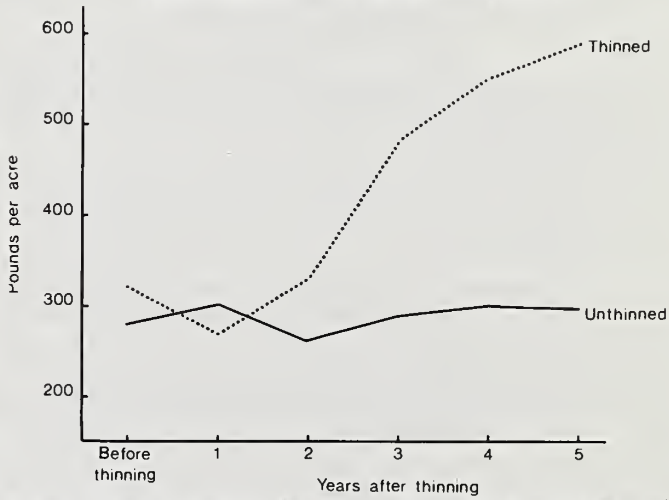

Figure 11.--Dry weight understory plant production (pounds per acre) before and after thinning to growing stock level (GSL) 40 in pole-sized Pinus contorta.

block suggests that these sites may be prime candidates for forage enhancement treatments.

Pinus contorta Stocking Control

Plant production and related understory components were monitored before and after treatments to control growing stock levels (GSLs) in 60-year-old *P. contorta* growing at the lowest elevations on the Experimental Forest (Crouch 1986) (figs. 10 and 11). Vegetation on most of the area resembled *P. contorta/V. scoparium* and *P. contorta/Carex geyeri* plant communities as described by Hess and Alexander (1986).

Plant production, cover, crude protein content, and digestibility all increased over 5 years at the lower GSLs 40 and 80, and were essentially unchanged on controls and GSL 120 plots.

According to numbers of fecal groups, deer and cattle preferred the more heavily thinned blocks, but elk exhibited no preference among GSL categories.

Figure 12.--Shelterwood harvest in subalpine timber in central Colorado.

Figure 14.--Fence line in a Populus tremuloides clearcut shows effects of browsing by deer, elk, and cattle.

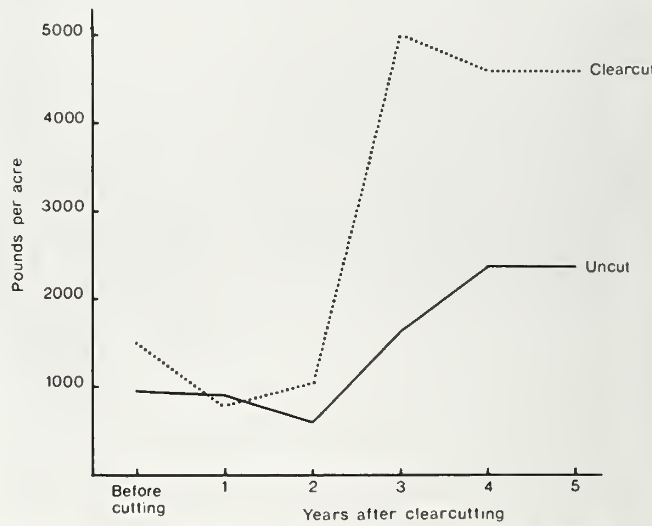

Figure 15.--Dry weight understory plant production before and after clearcutting in a stand of Populus tremuloides.

Ongoing Fraser Studies

Current studies consist mainly of continued monitoring of effects of the following treatments on vegetative components and big game activity.

1. Small-block clearcutting in mature *A. lasiocarpa/V. scoparium* and *A. lasiocarpa/Senecio triangularis* habitat types.
2. The first entry of a three-step shelterwood harvest in mature *A. lasiocarpa/V. scoparium* habitat types (figs. 12 and 13).
3. Clearcutting in mature *P. contorta/V. scoparium* and *P. contorta/Shepherdia canadensis* habitat types.
4. Clearcutting and partial cutting in a single stand of pole-sized *Populus tremuloides* (figs. 14 and 15).

Other Ongoing Studies

Forest Service big game habitat research elsewhere in the subalpine forests in the central Rocky Mountains is being conducted in aspen stands at five locations in western Colorado (fig. 16). On these sites, effects of aspen regeneration practices, including commercial clearcutting, on vegetative components and big game activity are being investigated.

Figure 13.--Dry weight understory plant production before and after shelterwood harvesting.

Related Previous Research

Earlier research on deer and elk feeding and use of subalpine habitats has been conducted elsewhere in the central Rocky Mountains. Nichols (1957), Harris (1958), and Boyd (1970) studied elk on summer and winter ranges on the White River Plateau, about 75 miles west of the Fraser Forest. More recently, elk and deer diets and habitat use were studied intensively in subalpine habitats in northern Utah, about 300 miles northwest of the Fraser Forest (Collins et al. 1978; Deschamps et al. 1979; Collins and Urness 1979, 1983).

One hundred miles north of the Experimental Forest in the subalpine forests of southern Wyoming, a series of studies determined effects of road building, logging, cattle grazing,

and other disturbance factors on elk and their habitats (Ward 1973, 1976; Ward et al. 1973).

Finally, Hobbs and others, working in nearby Rocky Mountain National Park, determined the composition and quality of elk winter and summer ranges (Baker and Hobbs 1982, Hobbs et al. 1981). Also estimated were elk winter range carrying capacities based on energy and nitrogen characteristics of the diets (Hobbs et al. 1982).

SUMMARY

Subalpine forests similar to those at Fraser provide growing-season habitat for deer and elk but are unsuitable as winter range, primarily because of deep snow and secondarily because they lack tall- and mid-height shrub understories. Their value as growing-season habitat also may be limited by the closed-canopy stands that dominate these ecosystems unless opened by fire or management activities.

However, as elsewhere, the critical factor regarding improvement of the capability of subalpine forests to support more deer and elk is the inability of their off-site winter ranges to support more animals, especially during severe winters, such as those that periodically occur in the central Rockies. Segments of these forests apparently can also provide year-round habitat for moose, although the permanence of the population at Fraser has not yet been established.

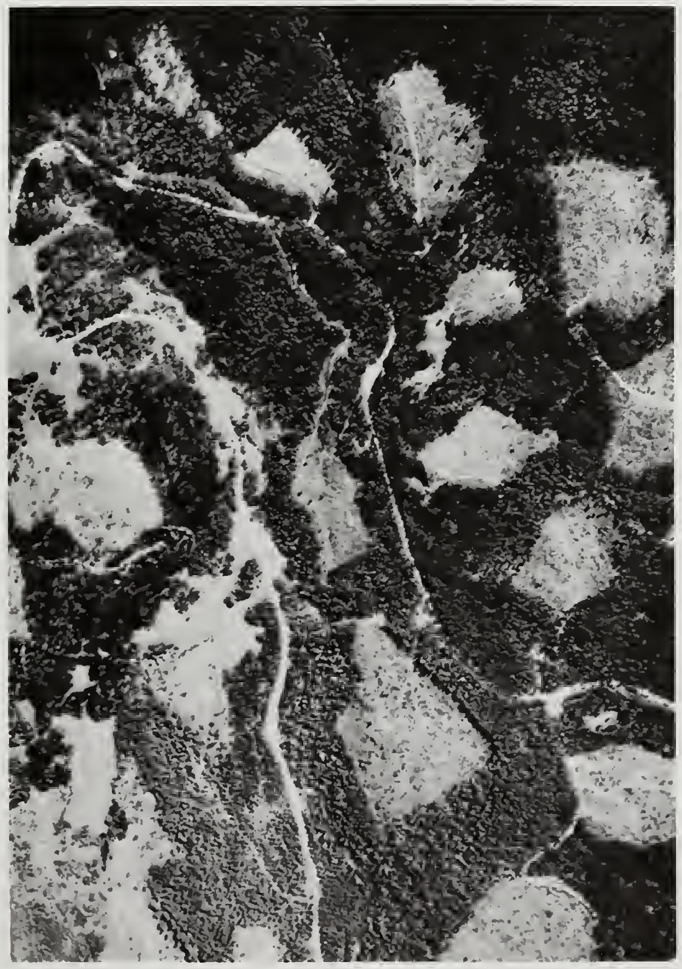

Figure 16.--Patch clearcut aspen timber sale on the San Juan National Forest in southern Colorado.

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Nongame Wildlife Research in Subalpine Forests of the Central Rocky Mountains

Martin G. Raphael[1]

Abstract--Subalpine forests of the central Rocky Mountains provide habitat for 145 species of amphibians, reptiles, birds, and mammals. Perhaps because of extreme seasonal climate and the relatively simple structure and composition of subalpine forest, diversity of wildlife is lowest of any forest type in the region. No species are found only in subalpine habitats but some, e.g., southern red-backed vole, reach their maximum abundance there. Research to date has emphasized community structure; much additional work is needed to understand population dynamics and habitat relationships of species that find optimum habitat conditions in subalpine forests.

Subalpine forests of Engelmann spruce, subalpine fir, and lodgepole pine cover about 5 million ha of forest land in Colorado and Wyoming and account for over 90% of sawtimber volume (USDA Forest Service 1980). The climate of the subalpine zone is harsh. Subalpine forests occur at elevations ranging from about 2,700 to 3,600 m where the mean annual temperature is about 2°C. Annual temperature variation is extreme, ranging from -45°C to over 30°C. Annual precipitation varies from 50 to 90 cm, falling primarily as snow from October through May. The frost-free period is very short, usually less than 60 days.

As a result of these harsh conditions, subalpine forests are rather simple in composition and annual productivity is low. Engelmann spruce and subalpine fir are usually codominant although one species may dominate in some stands. At lower elevations and on drier sites, lodgepole pine is often associated with spruce and fir and, on southerly slopes, sometimes occurs in pure stands. Understory cover is usually sparse, consisting primarily of common juniper and grouse whortleberry.

The purposes of this report are to (1) summarize field studies of the occurrence of nongame wildlife species in subalpine forests, (2) compare the fauna of subalpine to other Rocky Mountain forest habitats, (3) compare the fauna of the Rocky Mountains with that of coniferous forests in other regions in North America, (4) briefly summarize the status of our knowledge of habitat associations of subalpine wildlife, and (5) to summarize results of studies documenting the responses of these species to habitat disturbance caused by fire and logging.

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THE SUBALPINE VERTEBRATE COMMUNITY

Diversity of wildlife in subalpine forests is the lowest among habitat types in the central Rocky Mountain region (fig. 1). Hoover and Wills (1984) list 5 amphibian species, no reptiles, 38 mammals, and 76 birds that occur in subalpine forest of Colorado. If lodgepole pine (which is considered a separate habitat type by Hoover and Wills) is included within subalpine, a total of 5 amphibian, 2 reptile, 93 bird, and 45 mammal species occur in the combined habitat types in Colorado (fig. 2). The Wyoming Wildlife Database (Anderson and Patterson 1983) includes 2 amphibians, 4 reptile, 83 bird, and 52 mammal species that occur in subalpine forest of Wyoming.

Not only is the diversity of vertebrates low in subalpine forest compared to other habitat types in the Rocky Mountain region, vertebrate diversity in coniferous forests of the Rockies is low compared to other North American regions. When Wiens (1975) compared numbers of bird species reported in censuses conducted in Rocky Mountain conifer habitats to averages in the northeast, southeast, northern, Sierra Nevada, and northwest coastal forests, he found that Rocky Mountain forests supported an average of 14.0 bird species compared to 14.5-22.6 species in the other regions.

Most of the vertebrate species listed for subalpine habitats also occur in other forest habitats (figure 2, after Hoover and Wills 1984: Appendix A). For example, if one compares the list of species in subalpine habitat to lodgepole pine (fig. 2), most of the species for the combined habitats occur in both. A lesser number occur in lodgepole but not subalpine, and still fewer occur in subalpine but not in lodgepole. Among reptiles and amphibians, species overlap between subalpine and other

habitats (number of species occurring in both habitats divided by the total species occurring in the two habitats) was greatest with aspen and high elevation riparian habitats (71% each) and lowest with ponderosa pine (22%). For both birds and mammals, overlap was greatest with lodgepole pine (76% for each group) and, as was the case for reptiles and amphibians, lowest for ponderosa pine (53% for birds, 44% for mammals). Thus, few species occurring in subalpine habitat are unique to that type.

The overall similarity of wildlife species (percentage of species shared) among Rocky Mountain habitats is shown in figure 3. Subalpine and high elevation riparian habitats are most similar for reptiles and amphibians, followed by aspen, Douglas-fir, and lodgepole pine. These habitats form one related group that is only slightly similar (20%) to the remaining habitats. The overall clustering of habitats for birds and

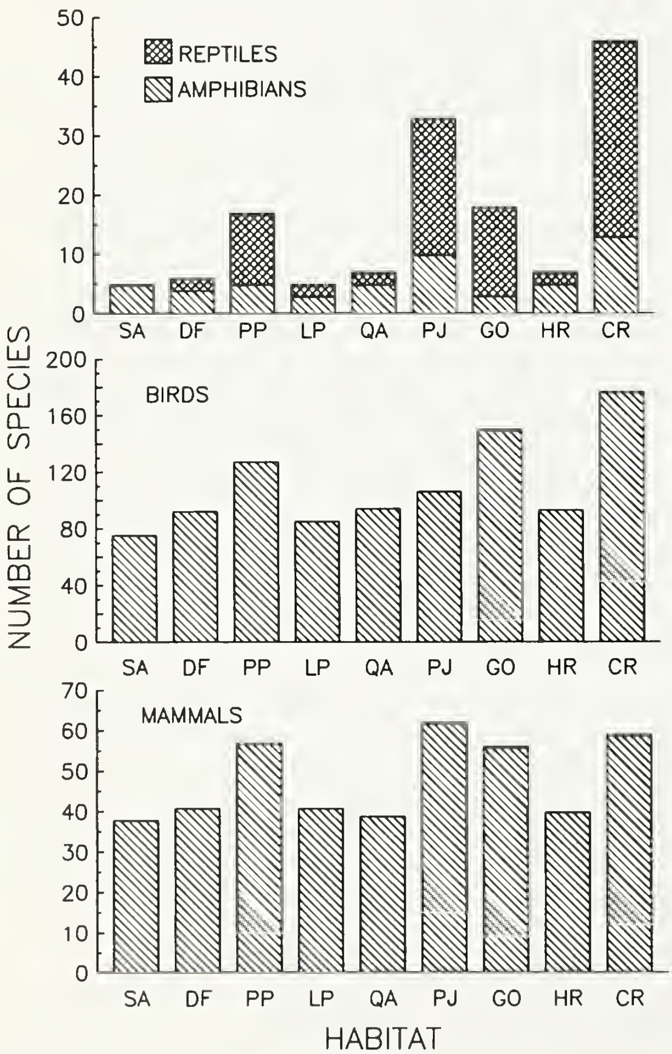

Figure 1.--Number of species of reptiles, amphibians, birds, and mammals in Colorado habitats (SA = subalpine, DF = Douglas-fir, PP = ponderosa pine, LP = lodgepole pine, QA = quaking aspen, PJ = pinyon juniper, GO = Gambel oak, HR = high elevation riparian, CR = cottonwood riparian). Data from Hoover and Wills (1984).

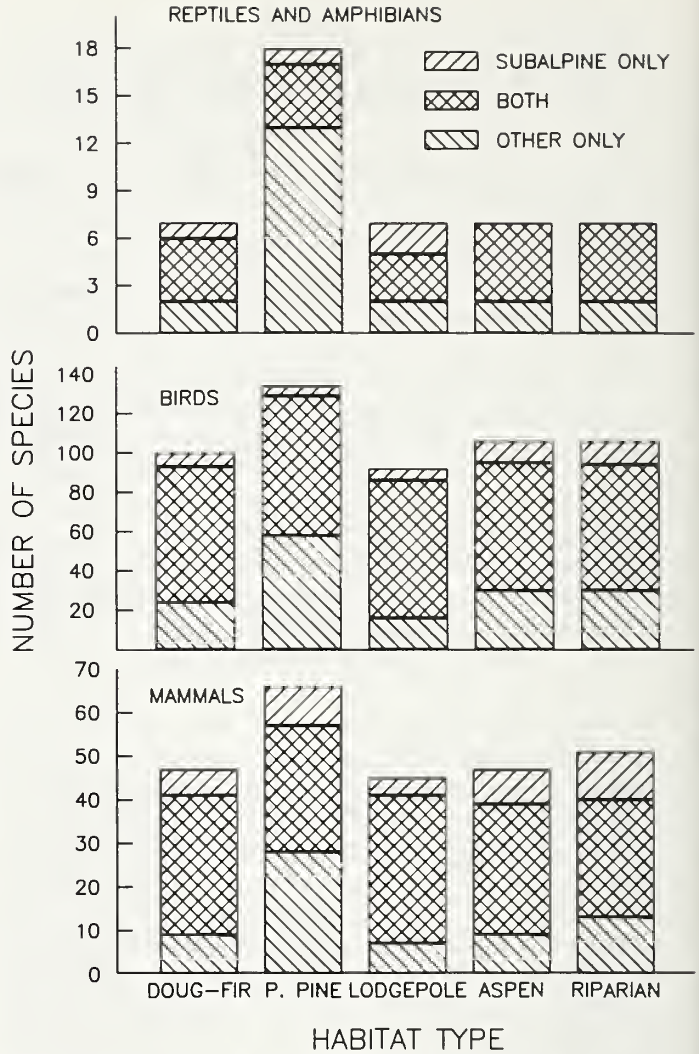

Figure 2.--Comparisons of species composition of subalpine forest with other forest types in Colorado (crosshatching indicates the number of species in common between subalpine and each other habitat type).

mammals follow a similar pattern, except that ponderosa pine is included with the subalpine group for birds. These cluster analyses show that wildlife species are fairly similar between the high elevation conifer, aspen, and riparian habitats and are similar between a lower elevation juniper, oak and cottonwood habitats but that the two groups of habitats share few species.

To better characterize the bird community associated with subalpine habitats, I reviewed all available published census data for the central Rocky Mountain region. This review yielded 19 studies which report occurrence of birds from a total of 54 sites described as subalpine forest. These studies reported 75 bird species, almost half of which were rare, occurring on fewer than 10 percent of the sites (table 1). Fourteen species occurred on 50 percent or more of the sites (table 2). Because these species are widespread among the sites included in this survey, they may be considered most typical of subalpine forest. It is interesting to note that most of

these species are also distributed throughout coniferous forests of North America (table 2). The most narrowly distributed species among those listed are mountain chickadee and Cassin's finch, which occur only in the Sierra Nevada in addition to the Rocky Mountains.

Most of these abundant species feed on insects or seeds in canopy foliage; lesser numbers forage on the ground or are timber drilling or searching. Wiens (1975) compared the distribution of birds among regions based on their foraging position (foliage, ground, timber, air) and found that foliage-feeding species dominated in all North American coniferous forests. Rocky Mountain birds, however, had the highest

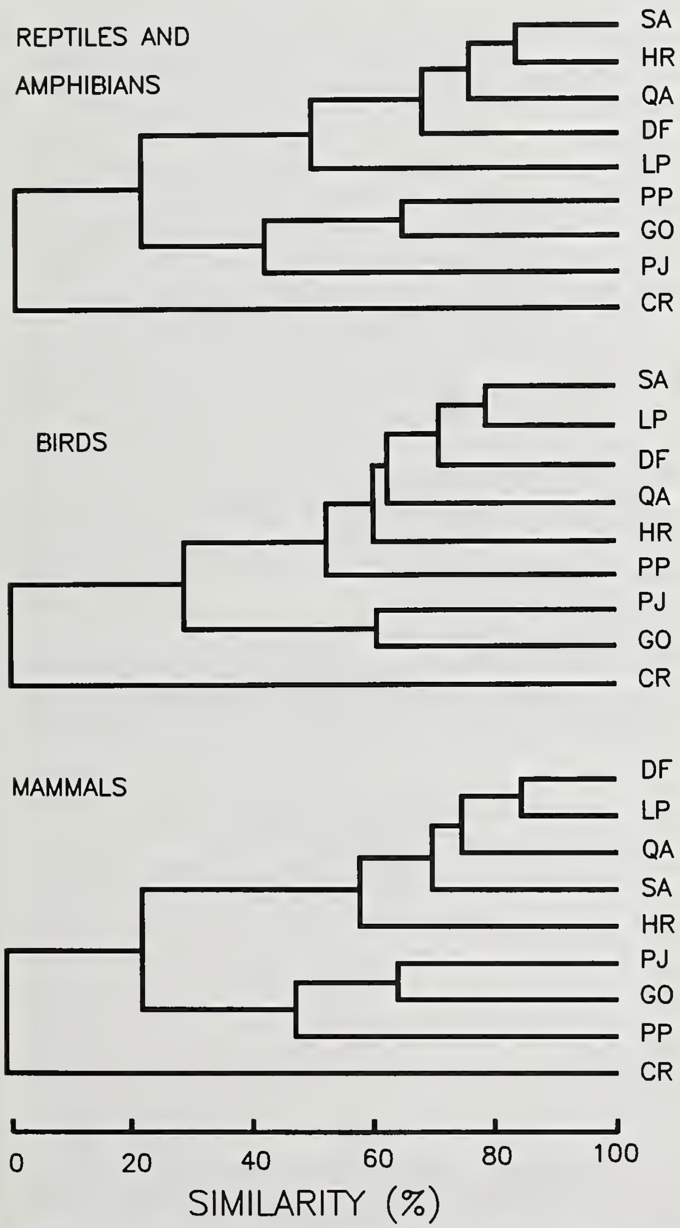

Figure 3.--Overall similarity (percentage of species shared) among Colorado habitat types (see figure 1 for abbreviations). Vertical lines joining groups indicate percent similarity of numbers of the group.

Table 1.--Frequency of occurrence (%) of bird species recorded during census of 54 subalpine forest plots in the central Rocky Mountains.[1]

Species	Percent occurrence among 54 sites
Northern Harrier *(Circus cyaneus)*	2
Sharp-shinned Hawk *(Accipiter striatus)*	6
Cooper's Hawk *(Accipiter cooperii)*	9
Northern Goshhawk *(Accipiter gentilis)*	9
Red-tailed Hawk *(Buteo jamaicensis)*	6
Golden Eagle *(Aquila chrysaetos)*	7
American Kestrel *(Falco sparverius)*	4
Merlin *(Falco columbarius)*	4
Blue Grouse *(Dendragapus obscurus)*	11
Ruffed Grouse *(Bonasa umbellus)*	7
Mourning Dove *(Zenaida macroura)*	20
Great Horned Owl *(Bubo virginianus)*	24
Northern Pygmy-Owl *(Glaucidium gnoma)*	4
Boreal Owl *(Aegolius funereus)*	2
Northern Saw-whet Owl *(Aegolius acadicus)*	2
Common Nighthawk *(Chordeiles minor)*	4
Broad-tailed Hummingbird *(Selasphorus platycercus)*	33
Yellow-bellied Sapsucker *(Sphyrapicus varius)*	19
Williamson's Sapsucker *(Sphyrapicus thyroideus)*	30
Downy Woodpecker *(Picoides pubescens)*	7
Hairy Woodpecker *(Picoides villosus)*	50
Three-toed Woodpecker *(Picoides tridactylus)*	14
Black-backed Woodpecker *(Picoides arcticus)*	4
Northern Flicker *(Colaptes auratus)*	44
Olive-sided Flycatcher *(Contopus borealis)*	30
Western Wood-Pewee *(Contopus sordidulus)*	26
Empidonax spp. *(hammondi* or *oblerholseri)*	35
Western Flycatcher *(Empidonax difficilis)*	20
Purple Martin *(Progne subis)*	6
Tree Swallow *(Tachycineta bicolor)*	20
Gray Jay *(Perisoreus canadensis)*	56
Steller's Jay *(Cyanocitta stelleri)*	15
Clark's Nutcracker *(Nucifraga columbiana)*	39
Black-billed Magpie *(Pica pica)*	6
American Crow *(Corvus brachyrhyncos)*	6
Common Raven *(Corvus corax)*	6
Black-capped Chickadee *(Parus atricapillus)*	19
Mountain Chickadee *(Parus gambeli)*	93
Red-breasted Nuthatch *(Sitta canadensis)*	65
White-breasted Nuthatch *(Sitta carolinensis)*	6
Brown Creeper *(Certhia americana)*	46
Rock Wren *(Salpinctes obsoletus)*	4
House Wren *(Troglodytes aedon)*	19
American Dipper *(Cinclus mexicanus)*	2
Golden-crowned Kinglet *(Regulus satrapa)*	54
Ruby-crowned Kinglet *(Regulus calendula)*	81
Mountain Bluebird *(Sialia currucoides)*	13

(continued)

Table 1.--(continued).

Species	Percent occurrence among 54 sites
Townsend's Solitaire *(Myadestes townsendi)*	30
Swainson's Thrush *(Catharus ustulatus)*	31
Hermit Thrush *(Catharua guttatus)*	74
American Robin *(Turdus migratorius)*	83
Cedar Waxwing *(Bombycilla cedrorum)*	2
Warbling Vireo *(Vireo gilvus)*	24
Yellow Warbler *(Dendroica petechia)*	6
Yellow-rumped Warbler *(Dendroica coronata)*	91
Ovenbird *(Seiurus aurocapillus)*	2
MacGillivray's Warbler *(Oporornis tolmiei)*	9
Wilson's Warbler *(Wilsonia pusilla)*	6
Western Tanager *(Piranga ludoviciana)*	46
Black-headed Grosbeak *(Pheucticus melanocephalus)*	6
Lazuli Bunting *(Passerina amoena)*	7
Green-tailed Towhee *(Pipilio chorurus)*	2
Chipping Sparrow *(Spizella passerina)*	52
Vesper Sparrow *(Pooecetes gramineus)*	2
Song Sparrow *(Melospiza melodia)*	7
Lincoln's Sparrow *(Melospiza lincolnii)*	22
White-crowned Sparrow *(Zonotrichia leucophrys)*	20
Dark-eyed Junco *(Junco hyemalis)*	96
Brown-headed Cowbird *(Molothrus ater)*	9
Pine Grosbeak *(Pinicola enucleator)*	57
Cassin's Finch *(Carpodacus cassinii)*	59
Red Crossbill *(Loxia curvirostra)*	31
White-winged Crossbill *(Loxia leucoptera)*	4
Pine Siskin *(Carduelis pinus)*	87
Evening Grosbeak *(Coccothraustes vespertinus)*	6

[1]*Sources included Snyder 1950 (2 sites), Thatcher 1956, Salt 1957 (3 sites), Webster 1967, Burr 1969, Kingery 1970, 1971, 1973, Winn 1976 (8 sites), Young 1977 (8 sites), Roppe and Hein 1978, Thompson 1978 (4 sites), Austin and Perry 1979 (2 sites), Harvey and Weaver 1979 (2 sites), Taylor and Barmore 1980 (3 sites), Smith and MacMahon 1981 (2 sites), Scott et al. 1982 (2 sites), Raphael (this symposium, 3 sites), Keller 1987 (10 sites).*

percentage (28%) of ground foraging birds and a lower percentage of foliage feeding birds (53%) compared with percentages of total density in other regions.

Total density of birds is low in Rocky Mountain coniferous forests compared with other regions (fig. 4). Wiens (1975) reported an average of 736 birds/100 ha (s.d. = 575) for all conifer habitats in the Rocky Mountain region. Among those studies reporting total density estimates (as summarized in table 1), I calculated a mean of 577 birds/100 ha (s.d. = 472, n = 31) which is lower than averages of all but the northern region (fig. 4).

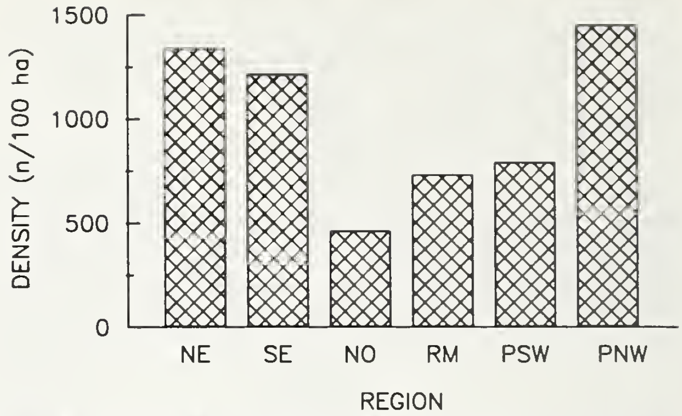

Figure 4.--Comparisons of abundance of birds among conifer forest regions in North America (NE = Northeast, SE = Southeast, NO = Northern, RM = Rocky Mountain, PSW = Pacific Southwest, PNW = Pacific Northwest), after Wiens (1975).

Biomass (total weight of all birds) averages 188 g/ha for all conifer forest types in the Rocky Mountain region (Weins 1975). For subalpine forests, I calculate a similar average of 187 g/ha based on data cited in table 1. Salt (1957) compared bird biomass in several habitat types and separated total biomass into that contributed by herbivores and carnivores (fig. 5). Biomass was much lower in subalpine forest types than in riparian, meadow, and aspen types, primarily because of the greater contribution of carnivores in the latter types. One possible explanation of this pattern is that insect biomass (primarily prey of carnivores) is greater in these habitats than in subalpine forest. In support of this argument, Schimpf and MacMahon (1985) found that insect density, diversity, and mean body size were all at least twice as great in aspen compared to subalpine forest.

Nongame mammals have received little study compared to efforts on birds. I found 11 studies enumerating small mammal faunas in subalpine forests of the Rocky Mountains (table 3). Altogether, these studies list 24 mammal species, of which only

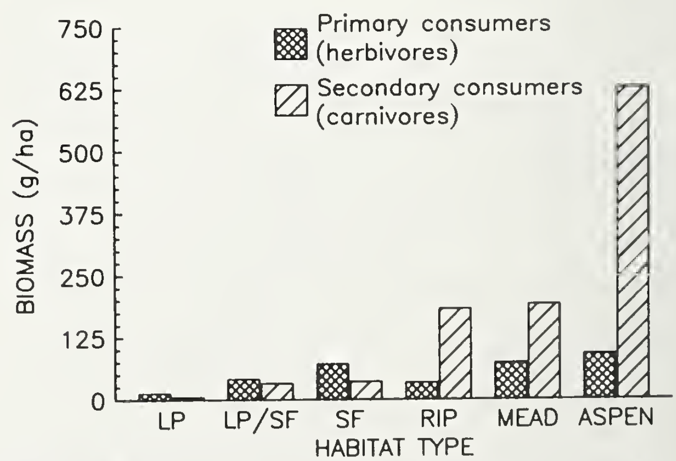

Figure 5.--Biomass of birds among habitat types in Wyoming (LP = lodgepole pine, LP/SF = lodgepole and spruce-fir, SF = spruce-fir, RIP = riparian, MEAD = meadow, after Salt (1957).

Table 2.-- The 14 most commonly reported bird species from subalpine sites (n = 54) in the central Rocky Mountains.[1]

Species	Frequency	Foraging Guild	Distribution[2] NE	SE	NO	SN	PN
Dark-eyed Junco	96	ground-seed	X	X	X	X	X
Mountain Chickadee	93	foliage-insect	X				
Yellow-rumped Warbler	91	foliage-insect	X	X	X	X	
Pine Siskin	87	foliage-seed	X	X	X	X	X
American Robin	83	ground-insect	X	X	X	X	X
Ruby-crowned Kinglet	81	foliage-insect	X	X	X	X	
Hermit Thrush	74	ground-insect	X	X	X	X	X
Red-breasted Nuthatch	65	timber-searching	X	X	X	X	X
Cassin's Finch	59	ground-seed	X				
Pine Grosbeak	57	foliage-seed	X	X	X		
Gray Jay	56	foliage-seed	X	X	X		
Golden-crowned Kinglet	54	foliage-insect	X	X	X	X	X
Chipping Sparrow	52	ground-insect	X	X	X	X	X
Hairy Woodpecker	50	timber-drilling	X	X	X	X	X

[1]*See table 1 for citations.*

[2]*NE = northeast, SE = southeast, NO = northern, SN = Sierra Nevada, PN = Pacific northwest (after Wiens 1975).*

Table 3.--Frequency of occurrence of small mammal species among 29 sites in subalpine forests of the central Rocky Mountains.[1]

Species[2]	Frequency (%)	Species[2]	Frequency (%)
Unidentified Shrew (*Sorex* spp.)	31	Red Squirrel *(Tamiasciurus hudsonicus)*	48
Masked Shrew *(Sorex cinereus)*	14	Northern Flying Squirrel *(Glaucomys sabrinus)*	41
Dusky Shrew *(Sorex monticolus)*	14	Northern Pocket Gopher *(Thomomys talpoides)*	10
Water Shrew *(Sorex palustris)*	7	Deer Mouse *(Peromyscus maniculatus)*	93
Nuttall's Cottontail *(Syvilagus nuttalli)*	7	Southern Red-backed Vole *(Clethrionomys gapperi)*	86
Snowshoe Hare *(Lepus americana)*	34	Heather Vole *(Phenacomys intermedius)*	14
Least Chipmunk *(Tamias minimus)*	28	Meadow Vole *(Microtus pennsylvanicus)*	3
Colorado Chipmunk *(Tamias quadrivittatus)*	3	Montane Vole *(Microtus montanus)*	21
Red-tailed Chipmunk *(Tamias ruficaudus)*	17	Long-tailed Vole *(Microtus longicaudus)*	17
Uinta Chipmunk *(Tamias umbrinus)*	45	Western Jumping Mouse *(Zapus princeps)*	45
Columbian Ground Squirrel *(Spermophilus columbianus)*	3	Porcupine *(Erithizon dorsatum)*	7
Golden-mantled Ground Squirrel *(Spermophilus lateralis)*	28	Ermine *(Mustela erminea)*	10
		Long-tailed Weasel *(Mustela frennata)*	21

[1]*Williams 1955 (2 sites), Negus and Findley 1959 (2 sites), Brown 1967a,b (2 sites), Winn 1976 (8 sites), Austin and Urness 1977 (2 sites), Anderson et al. 1980 (2 sites), Ramirez and Hornocker 1981 (2 sites), Scrivner and Smith 1984 (4 sites), Palmer 1986 (2 sites), Raphael (these proceedings, 3 sites).*

[2]*Names follow Jones et al. 1982.*

2 (deer mouse and southern red-backed vole) occurred on over half of the 29 sites sampled; 17 species occurred on less than one-third of the sites. The deer mouse is distributed throughout North America in nearly every habitat, forested and nonforested. The southern red-backed vole occurs in forests of Canada, the Rocky Mountains, and the northestern states. In many of the studies listed in table 3, this species was the most abundant small mammal and seems to find subalpine forest as its optimum habitat (e.g., fig. 6).

Whereas fewer species of small mammals are sampled in subalpine forest compared with birds, biomass of mammals is much higher. Vaughan (1984) estimated biomass of mammals in subalpine meadows from 3,171 to 3,537 g/ha in a three-year study; Anderson et al. (1980) estimated values from 2,228 g/ha on a spruce site to 3,593 g/ha on a fir site. These values, though undoubtedly subject to large error due to difficulties estimating small mammal density, are an order of magnitude greater than values for birds (which averaged only 187 g/ha, and ranged from 69 to 611 g/ha). In contrast to birds, most of the biomass of small mammals (67%) is contributed by herbivorous species (Vaughan 1984).

HABITAT ASSOCIATIONS

General Relationships

Compared to forests in other regions in North America, subalpine forests of the central Rocky Mountain area have received little study regarding habitat relationships of nongame wildlife. Hoover and Wills (1984) summarize general principles and report abundance of management indicator species in seral stages of major forest habitat types (ecosystems) in Colorado. Similar tabulations are available for Wyoming (Bernard and Brown 1978, Findholt et al. 1981,

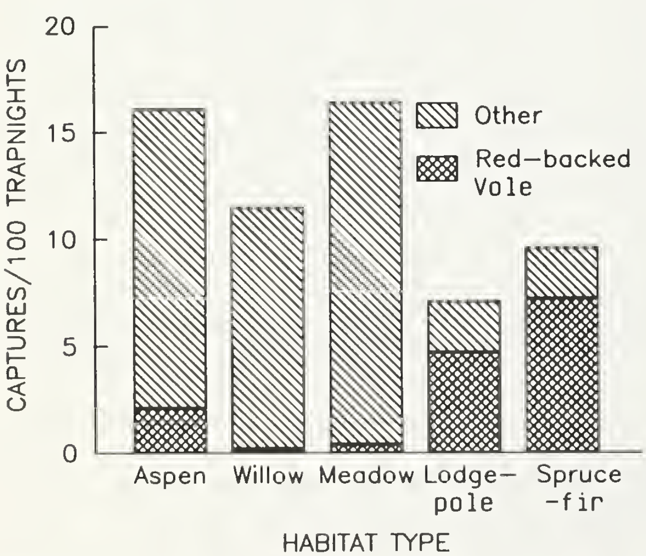

Figure 6.--Abundance of southern red-backed voles and other small mammal species in Rocky Mountain habitats (Brown 1967a).

Anderson and Patterson 1983, Baxter and Stone 1985) but these are based more on professional judgement and general ecology than on results of local research.

In one of the few bird community studies, Young (1977) examined bird diversity (numbers of breeding species) in relation to 14 structural features of subalpine forest. She found that diversity of tree diameters was the single best predictor of bird diversity ($R^2 = 0.73$); as diameter diversity increased, bird diversity increased. Winn (1976) found, in contrast, that plant species diversity was the best predictor of bird species diversity.

As summarized by Scott et al. (1980), cavity-nesting birds comprised about 25% of the total breeding density of birds in subalpine forest (range = 13-40%). Thus, the abundance and characteristics of snags is an important forest attribute. Scott et al. (1978, 1980) surveyed snags at the Fraser Experimental Forest in Colorado and found that lodgepole pine, Engelmann spruce and subalpine fir snags greater than 12 inches dbh were used for nesting at rates greater than expected from their availability, and that broken-topped snags of all three species also received the greatest use. Overall, only 3% of 1,722 snags sampled had nest cavities, but 33% of broken-topped snags > 12 inches d.b.h. had cavities.

Habitat associations of small mammals seem to have received more study, but detailed analyses of mammal communities in relation to habitat structure are lacking. The following examples illustrate typical studies from subalpine forests. Spencer and Pettus (1966) examined habitat associations of five shrew species. The presence of surface water was an important habitat feature. Dusky and dwarf shrews tolerated the most xeric conditions, masked and pygmy shrews were intermediate, and the water shrew was found only in close proximity to water. Brown (1967b) found a much greater abundance of masked shrews in boggy habitats, whereas dusky shrews were predominant in upland sites and pygmy shrews were associated with rock outcrops. The importance of moisture was also noted by Armstrong (1977).

Brown (1967a) related abundance of mice to proximity of water and cover density. Jumping mice and long-tailed voles were more abundant near water; montane voles, southern red-backed voles, and deer mice were more abundant on sites further from water (> 175 m away). Jumping mice, long-tailed voles, and montane voles were most abundant in dense understory cover; red-backed voles and deer mice were about equally abundant in all cover classes. Sleeper (1979) examined small mammal population fluctuation in relation to snowpack over a 6-year period, and found significant and negative correlations between summer population numbers and snowpack the previous winter for five mammal species. Deep snowpack appeared to depress population numbers. In a detailed study of the winter ecology of the southern red-backed vole, Merritt (1976, 1985) and Merritt and Merritt (1978) found that autumn freeze and spring thaw were periods of greatest hardship and poorest survival. Telleen (1978) compared the distribution of least and Uinta chipmunks at Rocky Mountain National Park, and reported that the Uinta

chipmunk preferred closed canopy forest with an open understory, whereas the least chipmunk favored open canopy and closed understory.

Studies of habitat associations of reptiles and amphibians are virtually nonexistent in subalpine forest, primarily because reptiles and amphibians are virtually nonexistent. Baxter and Stone (1985) have summarized habitat associations of subalpine species in Wyoming; Hammerson and Langlois (1981) do so for Colorado, but their habitat descriptions are limited to lists of habitat types in which each species is known to occur. Haynes and Aird (1981), in one of the more detailed analyses of habitat requirements, found that the wood frog breeds primarily in small (< 0.25 ha) natural ponds with emergent vegetation along a shallow north edge.

Responses to Disturbance

Fire

Fire-induced secondary succession in subalpine forest systems is accompanied by marked changes in bird and small mammal populations (Taylor 1971, Davis 1976, Roppe and Hein 1978, Ramsden and Lyon 1979, Taylor and Barmore 1980). In general, these studies show that biomass of birds and small mammals is greater in burned compared with unburned forest. Overall, biomass of birds is highest within the first 10 years following fire, then decreases during the intermediate period from 50-100 years following fire when, in the absence of further disturbance, stands are often overstocked and stagnated (fig. 7). Biomass increases thereafter to prefire levels. The general pattern varies, however, among birds in various feeding categories. Ground-foraging and timber-drilling birds are more abundant in burned forest, but seed- and insect-eating birds associated with the overstory canopy are more abundant in unburned forest (Taylor and Barmore 1980).

Similar patterns are also found among small mammals. Roppe and Hein (1978) estimated a biomass of small mammals of 1,020 g/ha on an 8 year-old burn compared to 764 g/ha in unburned forest. Red squirrels and showshoe hares, not counted in these totals, were absent in the burn. Shrews, golden-mantled ground squirrel, deer mouse, heather vole, and long-tailed vole were all more abundant on the burned plot, whereas southern red-backed vole was rare on the burn and abundant in the unburned forest. Chipmunks were equally abundant in both burned and unburned habitats. Taylor (1971) found that small mammal biomass, like that of birds, was lowest during the intermediate period of postfire succession (fig. 7).

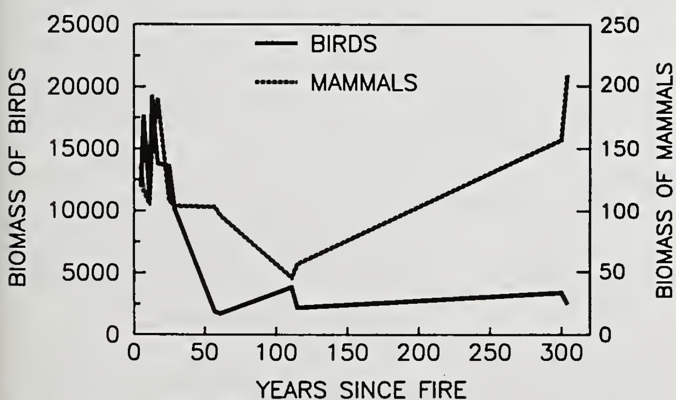

Figure 7.--Biomass (g/40) of birds and small mammals on various burned study areas (Taylor 1971).

Timber Harvest

Birds seem to respond to timber harvest in patterns similar to their responses to fire. Austin and Perry (1979) found much higher densities of birds in 25- and 15-year-old clearcuts (302 and 538 birds/100 acres, respectively) than in mature forest (134 birds/100 acres). Most of these differences were due to higher abundance of American robin, Cassin's finch, pine siskin, and chipping sparrow on the clearcuts. These are ground-foraging seed and insect eaters that are favored by opening the overstory canopy. In this study, only the hermit thrush (a ground-insect forger that nests in closed canopy format) and ruby-crowned kinglet (a canopy-insect forager) were more abundant in the mature forest.

Scott et al. (1982) found no significant short-term change in total numbers of birds during 2 years immediately after 36% of a 40-ha timber stand was harvested in 12 small clearcuts on the Fraser Experimental Forest. They did find significant declines in abundance of golden-crowned and ruby-crowned kinglets; no birds increased significantly, but the Lincoln's and song sparrow were observed on the harvested drainages following treatment but had not been observed prior to treatment.

The influences of slash disposal and other site preparation practices on the post-harvest suitability of stands were studied by Davis (1976). He found that increased logging residue, standing dead timber, and understory plant diversity all led to higher abundance of birds on clearcuts. Keller (1987) compared bird abundance in subalpine forest fragmented by recent stripcuts or small patchcuts and compared results to unharvested controls. She identified 6 species that were less abundant in timber adjacent to harvest in at least 1 year during her 2-year study, 4 that were more abundant, and 3 that showed no change. She concluded that brown creeper and red-breasted nuthatch (bark foraging species) were most sensitive to nearby harvest through reduction in their total foraging habitat area.

Studies of small mammal populations following harvest show variable results. Several studies report a net decrease in total abundance on clearcut sites compared to uncut sites (Porter 1959, Spencer and Pettus 1966, Austin and Urness 1977, Scrivner and Smith 1984), two studies report a net increase (Davis 1976, Ramirez and Hornocker 1981), and two studies showed no net change Campbell and Clark 1980, Scott

et al. 1982). The response of individual species was more consistent. Southern red-backed voles, for example, are consistently reported as much lower or absent in clearcuts, whereas deer mice, vagrant shrews, and least chipmunks are consistently more abundant in clearcuts. As reported among birds, site preparation and the nature of residual vegetation following logging are important in determining the suitability of post-harvest habitat for small mammals. Several studies (e.g., Davis 1976, Campbell and Clark 1980, Ramirez and Hornocker 1981) found a greater abundance of small mammals on clearcut sites with greater volume of slash or with thicker residual understory vegetation.

CONCLUSIONS

Studies of nongame wildlife in the central Rocky Mountains reveal that subalpine forests support low numbers of species and low population sizes of most species relative to other habitat types in the Rockies, and relative to other coniferous forest systems in North America. This rather depauperate fauna may be due to climatic extremes typical of the subalpine zone and the resulting low productivity of the forest. The few species that are abundant in subalpine forests tend to be widespread in distribution and are abundant in other forest types as well. Several species, including birds listed in table 2 and mammals such as the southern red-backed vole and marten, reach their peak in subalpine forest. Because of the extreme climate and the variability of snowfall and other weather factors from year to year, annual variation of population sizes of subalpine wildlife is great, suggesting that those species that winter in subalpine habitats may more often be limited by abiotic factors than by habitat.

Habitat associations of subalpine wildlife have received some study, but a great deal more research is needed. In particular, I found no studies of habitat associations of bats, a group that includes 14 species in Rocky Mountain forests but about which very little is known. There have been no long-term studies of nongame populations in relation to vegetation succession following fire or logging. Detailed quantitative studies of forest structure in relation to vertebrate community structure are lacking although some studies are underway. Much better information is needed on the distribution and occurrence of nongame wildlife species in the National Forests and Parks. The recent study by Newmark (1987), purporting to show evidence of losses of up to 43% of the original species among 14 National Parks in western North America, highlights the need to conduct a well-organized survey or inventory of the status of vertebrate species in our managed lands.

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Do We Know Enough to Manage Subalpine Wildlife Habitats? -- It All Depends

Jack Ward Thomas[1]

Abstract.--Subalpine ecosystems in the west have been largely immune from management action save grazing and recreation management. This situation has changed as access to such areas has improved and perceived demands for products of water, wood, wildlife, forage, and recreation have increased. Very little ecological research has been conducted in this ecosystem compared to lower elevation systems. Management of these areas, however, seems unlikely to be deterred by this relative paucity of detailed knowledge of ecosystem function. The political decision is to proceed with manipulation of these ecosystems and it is essential to bring the best knowledge available to bear on the issue and to proceed post haste with intensified research in the areas where knowledge is most critical and most lacking.

The question--do we know enough to manage subalpine wildlife habitats--should be expanded to include the adequacy of our knowledge to manage subalpine ecosystems for any purpose. Whether that management is labeled forest, watershed, wildlife habitat, or something else matters little. It seems that the time for management of subalpine ecosystems has come. These ecosystems have been largely excused from all but grazing and recreation management in the past because of their high elevation; relatively low annual biomass production; better, more abundant similar resources at lower elevation on more gentle terrain; lower demands for the resources available from such land, and--most of all--the lack of access for people and machinery to such areas.

Inexorably, these circumstances have changed and the opportunity and an increasing likelihood for management (i.e., manipulation) now exists. If past is indeed prologue, opportunity equates, sooner or later, to management to some degree for some purpose. Remember the cry of the seekers in the children's game of hide and seek when the count down was finished? "Here we come! Ready or not!" Just when we know enough to manage lies like beauty, in the eye and mind of the beholder.

As knowledge is never perfect nor complete nor adequately synthesized, there is risk in any land management action of damaging the ecosystem involved--perhaps irretrievably. There seems to be an array of interest groups when it comes to how much such risk is acceptable when breaking new ground in forest management. Those groups with the most to gain seem the most willing to take risks, and those with the most to lose are the least willing to risk much. Scientists, of course, are the most conservative of all, for two reasons. First, they probably perceive more complexity and unknowns in forest management than others. And second, they are more aware of just how unlikely it is that ecosystem response to management actions can be accurately predicted over the long run due to the cumulative effects of one management action after another after another over a prolonged period. The question of cumulative effects of management looms like a specter in the fog--not clearly discernable, but none-the-less formidable, and enough to instill a profound sense of caution.

A quick perusal of the literature suggests that we know much less about ecosystem function--certainly about wildlife habitat--in the subalpine areas of the West than we do about lower elevation ecosystems. This is probably due to the same reasons, mentioned earlier, that we are just now moving to management of such areas. There is one other reason--support for research in the subalpine ecosystems has been sparse. Research activities in ecosystem function and forest biology have been concentrated on lower elevation ecosystems where land management manipulations have been more fully implemented, problems have clearly emerged, and there is demand for better understanding of the situation.

It is difficult to obtain research support to develop knowledge ahead of the need for such knowledge. However, management action in the absence of adequate knowledge always either produces problems that need solutions, or creates the need for more specifics, such as coefficients to be used in

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models--or both! These problems or needs then generate the required political support for research. That seems generally the case with subalpine ecosystems. There has been inadequate research to minimize risks and maximize predictive capabilities from results of management action. Yet, the time for increasing management of subalpine systems seems at hand.

There are exceptions, fortunately, and the research that has been conducted on the Fraser Experimental Forest is one. The perceived need for increased water supplies for the developing megalopolis along the foothills of the eastern Rocky Mountain front provided the impetus for research to determine how to manipulate subalpine forests to enhance water flows, or control timing of those flows. The wildlife researchers who were able to piggy-back wildlife research studies onto these experimental timber manipulations (see Crouch, this symposium) should be commended for their foresight in seeing the ultimate need for such information, and for their ability and willingness to exploit the situation.

But, the question still remains--do we know enough to manage subalpine wildlife habitats?--without definitive answer. The answer must be that it all depends on the circumstances. For the wildlife biologist or any other resource management professional, this is akin to the much-maligned concept of situational ethics.

Let me illustrate from my own experience. The fir forests of the Blue Mountains of Oregon and Washington were hard hit by an outbreak of Douglas-fir tussock moth during 1971-1974. It was deemed necessary to salvage timber on large areas of essentially virgin forests. Four Forest Service forest supervisors asked to meet with me and a group of biologists from the Forest Service and Oregon Department of Fish and Wildlife. They described the impending salvage program, and asked advice on how the program might be modified to yield the best possible result in terms of wildlife habitat. As spokesman for the biologists, I decried the paucity of information available on wildlife habitat relationships in the vegetative types concerned, and concluded that the salvage action was premature. The senior forest supervisor, rather politely, informed me that they were not asking us for permission to conduct salvage logging. That decision had been made. They were asking for help with detemining how the operations would take place. If we had nothing to contribute, they would proceed considering advice from other natural resource specialists who did have something to say.

The biologists called "time out" and went into a huddle. Given the choice between participating in the design of the salvage operation and standing aside, we quickly decided, considering the alternatives, that enough was known to manage the affected wildlife habitats. Did we know enough to manage the wildlife habitats concerned? The answer, obviously, depended on the circumstances. We concluded it would be far better to combine our efforts and put forward the best synthesis of existing knowledge and experience concerning wildlife habitats we could, rather than stand aside decrying the miserable state of knowledge. In the final analysis, after the salvage operations were complete, the participants were convinced that wildlife habitat considerations were much better served than they would have otherwise been.

These initial guidelines for considering wildlife habitats during the salvage of tussock-moth-damaged timber eventually evolved into Wildlife Habitats in Managed Forests--the Blue Mountains of Oregon and Washington (Thomas 1979). This volume presented the available information on the relationship of resident terrestrial vertebrate species to plant communities and successional stages (or structural conditions), described special habitat features, and presented habitat modeling information for species to be featured in management. The publication has subsequently been credited as a stimulus for the Forest Service's ongoing Fish and Wildlife Habitat Relationships Program.

Since that time, similar efforts have been completed dealing with western Oregon and Washington (Brown 1985), the western Sierra Nevada mountains (Verner and Boss 1980), New England (DeGraaf and Rudis 1986), the Great Basin in Oregon (Maser and Thomas 1983), and Colorado (Hoover and Wills 1984) among others less formally published. A number of these efforts address, albeit peripherally, the habitat relationships of wildlife species resident in subalpine forests. Obviously, then, wildlife biologists do have some insights into how the impacts of various management actions in subalpine areas might be predicted and evaluated.

Perhaps the question should be--"Do we know enough to manage subalpine wildlife habitats with a high degree of confidence?" With, perhaps, the exception of a few species, the answer must be a rather emphatic "no." The information bases on wildlife habitat relationships mentioned earlier are a compilation of information and opinions from a variety of sources which may not be (1) specific to the subalpine ecosystems in question, or (2) particularly germane to the categorization of the data in the synthesis. Further, all the data and opinions used in the synthesis have been through the "filters" of the compilers of the synthesis, and colored by their training and experience. In many cases, gaps in existing published information (which are relatively large in the case of subalpine forests compared to lower elevation forests) were filled by a concensus of opinion of the participants in the synthesis process.

These synthesis efforts should be considered a beginning of the process to produce a state of knowledge necessary to allow management of subalpine habitats with a high degree of predictability in terms of ecological response. The participants in these pioneering synthesis efforts are, usually, the first to insist that these efforts be considered as working hypotheses--places to start, a guide to future research, and a good faith effort to participate in the unfolding drama of forest management. The alternative is to be either observers or largely unheeded critics.

These first efforts at synthesis of forest wildlife habitat relationships are probably weakest when it comes to dealing with subalpine ecosystems. Why? There is much less research done on wildlife habitat relationships in these forests than in

lower elevation forests. This relative paucity of information on wildlife habitats in subalpine areas--particularly as it relates to management manipulations of forests--should raise a flag of caution to managers. This flag of caution should be magnified in effect when it is considered that subalpine ecosystems in general (not just in terms of wildlife habitat), are relatively poorly understood.

It is obvious, however, that subalpine ecosystems are relatively fragile--the last transition from forests to the non-forested alpine zones. Such forests exist on relatively thin and poorly developed soils of low fertility, and endure severe climates and short growing seasons. Subalpine forests are much less forgiving of a manager's mistakes than the lower elevation forests that have provided most of our experience with forest and wildlife management.

So, we come again to the question--"Do we know enough to manage subalpine wildlife habitats?" The answer is "yes" and "no." We know enough to participate if management of such habitats is taking place. But, managers need to heed the whisper in their ears that warns that knowledge is not adequate to predict with confidence, over the long term, the effects of forest manipulation on most resident wildlife.

If there seems a high likelihood that subalpine forests of the mountain West will be manipulated within the foreseeable future for whatever purposes, it behooves us to concentrate more research effort on the entire subalpine forest ecosystem, not only in the area of wildlife habitat. It is likely that historians concerned about such things will identify the Fraser Experimental Forest as a cradle of such efforts. And, I hope they will say that what occurred up until 1987 was merely the beginning.

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A Preliminary Economic Assessment of Timber and Water Production in Subalpine Forests

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Abstract--Management costs and timber and water benefits of intensive management of a subalpine forest area in the Upper Colorado River basin were estimated. The water benefits were estimated with the use of a water basin model that indicated disposition of streamflow increases throughout the Colorado River Basin. This preliminary analysis indicates that the primary benefits of streamflow increases from intensive forest management in the Basin are in nonconsumptive water uses. The economic viability of intensive forest management was found to be very sensitive to costs of road construction and to estimates of values of water yield.

Watershed research has shown that vegetation management in some vegetation types can increase streamflow (e.g., Anderson et al. 1975, Hibbert 1979). Research at the Fraser Experimental Forest (Troendle 1983) in the spruce-fir type provides one of the most convincing examples of the potential for increasing water yield. Such research results have been received with interest by some water users in arid areas of the western United States, who look to application of the research results on an operational basis to alleviate current or expected water shortages (e.g., Cortner 1978).

An assessment of an operational program to increase water yield on public land should of course take into account the full set of costs and benefits in the context of multiple use management. The agency's monetary cost to implement such a program should be computed, and the onsite and offsite beneficial and adverse impacts should be estimated and valued. The onsite impacts include the effect on timber production, livestock grazing, wildlife populations, soil productivity, and scenic quality and recreation use. The offsite effects include changes in consumptive and nonconsumptive water use, changes in water quality, and lumber production. Thus, a comprehensive assessment of watershed management is a major effort.

Few published studies have analyzed the costs and benefits of watershed management for increased streamflow, and none have attempted a comprehensive assessment. For the spruce-fir type, however, two recent papers by scientists at Resources for the Future (Krutilla, Bowes, and Sherman 1983, Bowes, Krutilla, and Sherman 1984) have provided a good beginning. These papers compared the economic value of timber production and streamflow increases that would follow a vegetation management regime in the Colorado River Basin with the costs of management, including road construction costs.

This paper is also limited to impacts on timber and water yields. It builds on the Resources for the Future work (especially the paper by Bowes, Krutilla, and Sherman, or BKS) and another recent study that looked closely at the disposition of streamflow increases in the Colorado River Basin (Brown, Harding, and Lord, in press, or BHL). BHL modeled the storage, routing, consumptive use, and loss of flows in the Colorado River Basin with and without flow augmentation from vegetation management at the headwaters of the Colorado River. The difference between the with and without cases indicated the disposition of the additional streamflow.

The current study adopted the timber management regime and associated onsite yields posited by BKS, and the Colorado River water basin modeling of the BHL study. In addition, the effects of streamflow increases on two nonconsumptive water uses, hydropower production and dilution of total dissolved solids (tds), were estimated.

The paper first describes the timber treatment and its costs and yields. Next the water model is described, and the effects of streamflow increases on water use are presented. Then the timber and water yield increases with treatment are expressed in monetary terms, and the monetary costs and benefits of a vegetation management program are compared, first for

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current levels of water use and then for a future level. Finally, qualifications to the analysis are listed.

Timber Harvest

For this analysis, a lodgepole pine stand with a site index of 60 was assumed to be harvested on a 120-year rotation. Following road construction, one-third of this stand was harvested in small patches, followed by rapid natural regeneration. The harvested area received a precommercial thin in 30 years, commercial thins in 60 and 90 years, and a regeneration harvest in 120 years, whereupon the cycle would repeat itself. Thinnings were to a growing stock level of 80. Commercial harvests were of trees of at least 6.5 inches d.b.h., to a 6-inch top. From BKS, the four commercial harvests were assumed to yield 3.6, 2.6, 4.6, and 16.8 Mbf per harvested acre, respectively (table 1). Another one-third of the stand received these treatments beginning in year 30, and the final one-third received the treatments beginning in year 60 (see table 1 of BKS). On average, these treatments yielded 124 boardfeet per acre per year.

The following treatment costs, in 1982 dollars, were assumed: sale preparation and administration costs of $16 per Mbf (from BKS), precommercial thinning costs of $95 per acre (BKS), and logging and hauling costs for both commercial thins and regeneration harvests of $110 per Mbf (U.S. Forest Service Rocky Mountain Region records). The costs for the first one-third of the stand, ignoring road costs, are summarized in table 1. Costs for the other two – thirds are identical, but lagged 30 or 60 years. Costs of road construction, maintenance, and reopening received special attention by BKS because they vary so widely from one situation to another and because of the difficulty of choosing the most realistic road length and type, and the most likely slope of the terrain, for the study area. BKS's road costs, discounted at 4%, are reproduced in table 2.

Table 1.--Yield and cost for even-aged management of lodgepole pine stand.[a]

Year	Activity[b]	Yield[c] (Mbf/acre)	Cost[d,e] ($)
0	HVST	3.6	126/Mbf
30	PCT[e]	0.0	95/acre
60	THIN[e]	2.6	126/Mbf
90	THIN[e]	4.6	126/Mbf
120	HVST	16.8	126/Mbf

[a]Site index of 60.

[b]HVST is regeneration harvest, PCT is precommercial thin, and THIN is commercial thin.

[c]Trees 6.5 inches d.b.h. and larger to 6-inch top.

[d]1982 dollars, ignoring road costs.

[e]To a growing stock of 80.

Table 2.--Road cost per acre harvested by type of road, type of terrain, and length of road.[a]

Miles[b]	Type of road: Temporary	Intermittent	Seasonal	Surfaced
	Gentle slope (0.15%)			
2.5	47.47	70.61	99.83	121.07
3.5	66.46	98.86	139.76	169.50
4.5	85.43	127.11	179.69	217.93
5.5	104.41	155.36	219.62	266.36
6.5	123.39	183.61	259.55	314.79
7.5	142.37	211.86	299.48	363.22
8.5	161.35	240.11	339.41	411.65
	Moderate Slope (15.40%)			
2.5	64.19	77.56	107.62	128.89
3.5	89.86	108.59	150.69	180.44
4.5	115.54	139.62	193.75	232.00
5.5	141.21	170.65	236.81	283.55
6.5	166.88	201.68	279.87	335.10
7.5	192.00	232.71	322.93	386.65
8.5	216.47	263.74	366.00	437.47
	Steep Slope (<40%)			
2.5	91.64	96.91	138.89	167.94
3.5	128.29	135.68	194.44	235.13
4.5	164.94	174.45	250.00	302.31
5.5	201.59	213.22	305.56	369.49
6.5	238.24	251.99	361.12	436.67
7.5	274.89	290.76	416.68	503.84
8.5	311.54	329.53	472.24	571.02

[a]Reproduced from Bowes et al. (1984). Costs of road construction, maintenance, and reopening in 1982 dollars, discounted at 4%. Construction was assumed to be completed in year 0, before harvests began.

[b]Miles of road per square mile of land accessed.

Water Yield

The general approach to estimating the benefits of the streamflow increases was to determine the disposition of the flow increases, and then to assign marginal dollar values to the used water quantities. The disposition of the increases was determined by simulating water flow, storage, use, and loss within the entire Colorado River Basin (fig. 1) with and without the flow increases, and subtracting the "without" results from the "with" results. This was done for a 72-year period corresponding to available flow records.

Existing water storage and delivery facilities of the Basin were taken as given for the study. Management of these facilities was assumed to proceed according to existing legal and administrative institutions. Thus, intrastate water allocation was assumed to follow the doctrine of prior appropriation, and interstate allocation to follow existing compacts, court decisions, and administrative decisions, as described by BHL.

The Colorado River system was simulated with a linear programming network optimization model. The model, an adaptation of MODSIM (Shafer 1979, Labadie et al. 1983) and

Figure 1.--Colorado River Basin.

its predecessor SYMYLD (Texas Water Development Board 1972), uses the out-of-kilter algorithm (Clasen 1968, Barr et al. 1974) to perform a static optimization at each time step that mimics the system of priorities for water allocation in a river basin network. The model has three basic tasks: (1) manage input and output of data and control information, (2) convert a problem stated in hydrological terms into one amenable to solution by the out-of-kilter algorithm, and (3) use the algorithm to solve the network flow problem. The structure of the model is described by BHL, but some aspects of the model are summarized here.[2]

Water movement and disposition in the Colorado River Basin were modeled by aggregating sufficiently over time and space to conform to the limitations of the model. Each year was represented by four time steps representing the fall (October-December), winter (January-April), runoff (May-July), and irrigation (August-September) seasons. The Basin's 10 major reservoirs were represented by 7 reservoirs in the model. Consumptive use areas were combined into 22 points of use. Inflow, flow gains, and flow losses were combined into 21 points of natural flow change.

[2]The U. S. Bureau of Reclamation has a very detailed and complex simulation model of the Colorado River Basin, called CRSS (DOI 1985). For this application, the model described here was used because it was more tractable and more easily adapted to examination of the effect of flow increases. However, future interest in the routing of flow increases may warrant comparing the results of this analysis with those obtained using the BOR model.

Reservoirs and Hydropower Production

The reservoirs of the model contain a total live capacity of 60,028,000 acre-feet (table 3). Lake Mead was separated into its conservation and flood control portions to allow simulation of the separate operating rules that apply to the two storage categories. Hydroelectric power is produced at all reservoirs except Navajo. Energy production was modeled as a function of (1) the amount of water that passed through the turbines, (2) the feet of effective head that the water dropped, and (3) power plant efficiency, capacity, and minimum head (table 3). Overall hydraulic, mechanical, and electrical efficiency of all plants was assumed to be 90% (BKS). Energy production computations are listed in the Appendix.

The gross time step used in this study may have resulted in an unrealistically high estimate of hydroelectric power production. The capacity constraints were compared with flows from the dams for each period; some water may have been assumed to run through the turbines to produce power when it would in real time have been released via the spillways.

Table 3.--Reservoir storage and power production.

Reservoir	Live storage capacity[a] (1,000 acre.feet)	Generator[b] capacity (1,000 KW)	Min. head[c] (feet)	Max. head[c] (feet)
Upper Basin				
Fontenelle	250	10	80	110
Flaming Gorge	3,749	108	260	440
Blue Mesa	815	60	236	360
Morrow Point	115	120	353	430
Crystal	18	28	166	224
Navajo	1,696	--	--	--
Powell	25,002	1,206	385	568
Lower Basin				
Mead conservation	20,659	1,452	420	585
Mead flood control[d]	5,350	--	--	--
Mohave	1,810	240	89	136
Havasu	619	120	60	80
Total	60,082			

[a]Computed as total capacity minus dead storage.

[b]Source: Annual Report 1985, Western Area Power Administration (WAPA), U.S. Department of Energy.

[c]Source: Input parameters for the CRSS model (DOI 1982).

[d]Emptied in the fall season to simulate the requirement to provide at least 5.35 million acre.feet of flood control storage on January 1 of each year (DOI, 1982). Releases from this pool were also considered available for power production.

Reservoir evaporation was computed at the end of each time period from surface area/volume relationships and unit evaporation rates adopted from the U. S. Bureau of Reclamation's Colorado River Simulation System (CRSS) model (DOI 1982).

Total Dissolved Solids

Lower Basin salt concentrations, or total dissolved solids (tds), were computed by tracking salt mass and water volume entering, leaving, or remaining in Lakes Powell and Mead, plus salt and water entering the river below Lake Mead, in each time period. The relationships used for tds computations are included in the Appendix.

An average of 9 million tons of salt enter the Colorado River per year (DOI 1983). We assumed that this mass was constant per year, and that 8 million tons entered above Lake Powell and 1 million tons entered below Lake Mead. Furthermore, we assumed complete mixing of salts in Lakes Powell and Mead per period. In addition, we assumed that tds of the streamflow increases was 50 mg/l and that the tds of water stored in Lakes Powell and Mead at the beginning of the simulation was 678 mg/l, the mean tds level for the 1973 to 1983 period (Miller et al. 1986).

The assumptions of constant salt contribution each year and rapid mixing within the reservoirs are known to be incorrect. First, salt in return flows obviously varies with quantity withdrawn. Second, Mueller and Osen (1987) found that the quantity of dissolved solids entering the Colorado River Basin with natural (not return) flows varies with flow, and that the relationship between flow and salt contribution differs by location. Third, Gardner (1983) reports that, while relationships are not well understood, experts assume a lag of several years before a change in tds levels entering Lake Powell are realized in the Lower Basin. Accounting for these nuances was beyond the scope of this preliminary study; however, it should be noted that a lag in salt mixing in reservoirs would tend to spread the annual fluctuations in salt inflow over several years, so that the effect of one of our assumptions is counteracted by the other assumption.

Flows

"Normal," or pretreatment, flows were based on a 72-year period (1906-1977) of monthly reconstructed virgin flows developed by the USBR for 28 stations throughout the Basin. These data were combined to conform to the four seasons and 21 inflow points of the model.

Streamflow increases from vegetation management entered the network in the Upper Colorado River (fig. 1). Based on experience at Fraser Experimental Forest (Troendle 1983), the increases were assumed to come entirely during the runoff (May-July) period. The annual flow increase per acre was estimated as a product of (1) expected annual increase assuming average precipitation conditions and (2) a factor expressing the difference between actual and average precipitation conditions. The expected increases were taken from BKS, who computed them for the timber harvest regime described above based on the flow increase model of Leaf and Alexander (1975). The annual adjustment factors were computed as the ratio of annual to mean annual flow on the Colorado River at Glenwood Springs, downstream from the treatment area. Thus, the annual flow increase was assumed to be directly proportional to annual normal flow. For example, a year that experienced a normal flow 50% above average would also receive a flow increase 50% above the mean flow increase expected at that stage of the treatment regime.

To provide a realistic context for modeling, it was assumed that the 334,600 acres vegetated with harvestable species in harvestable areas that drain the Arapaho National Forest above Kremmling, Colorado (as delineated by BHL) were available for treatment, and that those areas all experienced the streamflow increases expected from harvest of the lodgepole stand described above. The Arapaho National Forest was chosen because of its significant precipitation and resultant potential for streamflow increases with vegetation management, and its proximity to the Fraser Experimental Forest, where the water yield model used to predict streamflow increases was developed. A large area was chosen in order to posit a sufficiently large streamflow increase for water basin modeling purposes.

Mean annual flow increases varied from 1.3 inches just before the 30th year of the timber management regime to 3.1 inches just after the 60th year harvests (BKS, table 4). Annual adjustment factors ranged from 0.38 to 1.91. When the per acre yields were then multiplied by the 334,500 acres assumed available for treatment, this procedure yielded annual flow increases that ranged from 15,611 to 101,434 acre-feet, with a mean of 55,583 acre-feet. The mean streamflow increase is equivalent to 0.4% of mean annual virgin flow at Lee Ferry over the historical flow record.

Water Requests and Allocation Priorities

The Upper Basin was represented by 15 consumptive use areas, corresponding to agricultural, municipal and industrial (M&I), and energy uses in each of 5 use areas: (1) the Upper Green River area above Flaming Gorge Reservoir in western Wyoming, (2) the Lower Green River area in western Utah, (3) the Yampa area in northwestern Colorado, (4) the Upper Colorado River areas near Grand Junction, Colorado, and including exports to the Colorado Front Range, and (5) the San Juan drainage area east of the Four Corners.[3]

Table 4.--Annual consumptive use requests for water under current and future conditions (1,000 acre-feet).[a]

Use area	Current	Future
Upper Basin		
Upper Green	354	673
Lower Green	674	1168
Yampa	155	198
Upper Colorado	1,761	2,369
San Juan	510	849
Total	3,454	5,257
Lee Ferry Flow-through	8,231	8,231
Lower Basin		
Arizona/Nevada Agriculture[b]	1,310	1,250
Arizona/Nevada M & I[b]	198	384
Central Arizona Project (CAP)[c]	765	1466[d]
California Agriculture	3,902	3,902
California Metropolitan Water District (MWD)	498	498
MWD Excess[e]	729	729
Total	7,402	8,229
Mexico	1,500	1,500

[a]Principal source: U.S. Department of Interior (1982). These several requests were apportioned to seasons, and assumed to be constant over the 72-year simulation.

[b]Located principally along the Colorado River.

[c]Including both agricultural and M & I uses.

[d]Computed as the difference between the total Arizona allocation (2,800,000 acre-feet) and the non-CAP Arizona diversion (1,334,000 acre-feet).

[e]Computed as the difference between the highest historical delivery by MWD (1,227,000 acre-feet) and MWD's authorized use under interstate agreement (498,000 acre-feet).

The Lower Basin area was represented by six water request areas, one for agriculture and one for M & I use in Nevada and Arizona along the Colorado River, one for southern Arizona via the Central Arizona Project (CAP), and three for California (table 4). The California areas distinguish (1) agricultural and (2) Metropolitan Water District (MWD) authorized use under the Boulder Canyon Act of 1928 (as reinforced by the 1963 U.S. Supreme Court decision in California vs. Arizona), and (3) use by MWD in excess of that act. Mexico is the other consumptive use area.

In addition to the consumptive use requests, a flow-through demand at Lee Ferry accounted for the Upper Basin obligation to the Lower Basin. This obligation reflects the apportionment established in the Colorado River Compact of 1922, and assumes that the Upper Basin contributes half of the Mexican delivery commitment.

Water was allocated within the Basin according the priorities established by interstate compacts, treaties with Mexico, court decisions, and operating rules for the storage and delivery of the water. The Lee Ferry flow-through and Mexico delivery obligations were satisfied first, followed by Upper Basin consumptive use requests. All Upper Basin consumptive use requests were given identical priority. Upper Basin reservoirs were filled after Upper Basin consumptive use requests were met, with reservoirs at higher altitudes filled first to minimize evaporation. Priorities of consumptive use in the Lower Basin reflected the U. S. Supreme Court's 1963 decision in Arizona vs. California. The Lake Mead flood control pool was satisfied last and was emptied in the fall season. To summarize, the priorities are as follows:

1. Lee Ferry delivery; Mexico delivery
2. Upper Basin consumptive uses
3. Upper Basin storage
4. Lower Basin consumptive uses except CAP and MWD excess
5. CAP use
6. Mead conservation storage
7. MWD excess use
8. Mead flood control storage

In keeping with current reservoir management in the Basin, priorities for water allocation for hydroelectric power production and Lower Basin salt dilution were not included in the network. Power production was assumed to be a subsidiary goal, which used water as it became available in the course of

[3]Aggregation of Upper Basin consumptive use into 15 use areas in the model may have caused shortages at some actual points of use to be overlooked. That is, although aggregate water supply of the use area may be sufficient to meet aggregate requests, the location of some actual points of use may be upstream of the actual water available to meet requests at those points.

meeting consumptive use requests in light of physical and institutional constraints on storage and delivery. Lower Basin tds was simply computed post hoc in order to estimate the cost to consumptive water users of the tds of their water.

Consumptive use estimates were taken largely from the monthly figures developed by the Bureau of Reclamation (DOI 1982) as input to the CRSS model. Upper Basin consumptive use requests currently total 3.5 Maf, and may reach 5.3 Maf in the future (table 4). The "current" levels reflect 1980 conditions, and the "future" levels reflect conditions that may exist in 2030 if current institutional arrangements remain unchanged and current Bureau of Reclamation forecasts are accurate. The requests are for consumptive use (i.e., diversion minus return flow). Mexico's consumptive use request of 1.5 Maf reflects the Mexican Water Treaty of 1944.

Three scenarios were simulated. Two of the scenarios assumed the current water request level and the third assumed the future request level (table 4). The two current scenarios differ in terms of the flexibility with which releases from Lake Mead are made to meet MWD water requests. Some flexibility is possible given the authority of the Secretary of the Interior to declare a surplus in Lake Mead and release water from the Mead conservation pool in excess of the release required to meet legal entitlements. Scenario 1 assumes a conservative interpretation of the Secretary of the Interior's discretion in such releases, limiting releases from the Mead conservation pool to meet California water requests to the legal entitlement of 4.4 million acre-feet. This policy does not allow any releases from the Mead conservation pool to meet MWD excess requests. Scenario 2 assumes that releases can be made to meet MWD excess requests if the Mead conservation pool is at least 75% full. Scenario 3 assumes the future water requests and the same flexibility in Mead releases as the second scenario.

Table 5.--Projected average annual Colorado River water disposition, hydropower production, and lower basin TDS levels.[a]

	Scenario 1: Current water requests without Mead flexibility[b]		Scenario 3: Future water requests with Mead flexibility[c]	
	Normal flows	Augm.[d] flows	Normal flows	Augm.[d] flows
Water disposition (1,000 af)				
Upper Basin				
Consumptive use	3,449	3,449	5,242	5,242
Shortage	2	2	17	17
Evaporation	749	750	628	634
Lower Basin				
Consumptive use	7,172	7,175	7,803	7,803
Shortage	225	222	422	422
Evaporation	1,455	1,460	875	888
Net change in reservoir content	37	39	.366	.343
Outflow to Mexico	3,296	3,341	1,978	1,991
Hydropower production (Million kWh)	14,944	15,009	11,971	12,058
Lower Basin TDS (mg/l)	628.7	626.4	689.6	687.4

[a]Reservoirs two-thirds full at beginning of simulation period.

[b]No releases from Mead conservation pool to meet MWD excess requests.

[c]Releases from Mead conservation pool to meet MWD excess requests if the pool is at least 75% full.

[d]Flows augmented by treatment of 344,600 acres on Arapaho National Forest.

Use of Streamflow Increases

Water allocation within the Colorado River Basin was modeled for a 72-year time span as if the 1906-1977 inflows were to repeat themselves beginning at the start of the simulations. Reservoirs were assumed to be two-thirds full at the beginning of the simulations, which understates current storage. The three scenarios were simulated with and without runoff increases that could be produced by applying the harvest regime described above to 334,600 acres of the Arapaho National Forest.

At current water request levels and without flexibility in releasing from Lake Mead to meet MWD excess requests (Scenario 1), shortages were substantial and concentrated in the Lower Basin. Upper Basin shortages averaged 2,000 acre-feet per year (table 5), and were restricted to the Yampa use area during the irrigation season in a few dry years. These shortages were not affected by the streamflow increases. Lower Basin shortages averaged over 200,000 acre-feet per year with or without flow increases, and were entirely in the MWD excess account. On average, 3,000 acre-feet per year of the increase was delivered to the MWD excess request account. This delivery is equivalent to 9 acre-feet per year per 1,000 acres of treatment (table 6). The increases did little to alleviate Lower Basin shortages because they seldom reached Lower Basin users during times of shortage. Because Lake Powell storage was sufficient to meet required releases to the Lower Basin without the flow increases, the increases accumulated in Lake Powell until they could no longer be stored. They were released or spilled from Powell during high flow years, which was typically when the Lake Mead conservation pool was also full and there were no shortages in the Lower Basin. Thus, the increases tended to flow on past Lower Basin diversions to Mexico. Occasionally, however, the streamflow increases were stored in the Mead flood control pool and released later the same year to meet MWD excess requests. On average, 5% of the increase was consumptively used, 11% evaporated, and 82% flowed to Mexico (table 6).

In addition, because the additional flow increased hydraulic head in Lakes Powell and Mead, and increased flow through the turbines, 194 more kilowatt hours (kWhs) were produced per acre of harvest. Finally, the flow increase

Table 6.--Projected average annual effect of vegetation treatment.

	Current water request level		Future water request level[a]
	Without flexibility in Mead releases (Scenario 1)	With flexibility[a] in Mead releases (Scenario 2)	(Scenario 3)
Timber production (bf/ac)	124	124	124
Water disposition (a-f/1,000 ac)[b]			
Consumptive use	9	0	0
Evaporation	18	38	57
Net change in storage	6	6	69
Outflow to Mexico	134	123	39
Total[c]	167	167	165
Hydropower production[b] (kWh/ac)	194	185	260
Reduction in Lower Basin[b] TDS (mg/l/1,000 ac)	0.007	0.006	0.007

[a]Releases from Mead conservation pool to meet MWD excess requests if that pool is at least 75% full.

[b]Based on treatment of 344,600 acres of the Arapaho National Forest.

[c]May not add to 166 because of rounding.

reduced Lower Basin tds levels by about 0.007 mg/l per 1,000 harvested acres (table 6).

With flexibility in Mead releases to meet extra-compact requests (Scenario 2), Lower Basin consumptive use requests were completely met, so the streamflow increases were not needed there. Upper Basin shortages were minimal, restricted to the Yampa use area, and not affected by the increases. Again, the increases were stored in Lake Powell until years of high flow, when they were released from Powell and tended to flow on to Mexico. Over the 72-year simulation, 74% of the runoff increases flowed to Mexico and 23% evaporated (table 6). Although not used consumptively, the flow increase raised hydraulic head and produced power upon passing through the turbines at Glen Canyon and Hoover Dams. The increase also lowered Lower Basin tds levels. On average, the increases produced 185 kWhs per harvested acre and reduced tds levels by 0.006 mg/l per 1,000 harvested acres (table 6).

At the future water request level, and with the flexible Mead release policy (Scenario 3), shortages averaged 17,000 acre-feet per year in the Upper Basin (table 5). The shortages occurred in several use areas, including the Upper Colorado. They occurred during the irrigation season only, however, so that the runoff increases were not available to offset them. Lower Basin shortages, all to the MWD excess account, were 422,000 acre-feet per year. They also were not affected by the flow increases because the shortages occurred during years when the Mead conservation pool was below the 75% cutoff for releasing to MWD excess.

Reservoir storage was considerably lower with Scenario 3 than with Scenarios 1 and 2 because of the higher consumptive use levels of Scenario 3. Because of the generally lower storage levels, much of the runoff increase with Scenario 3 accumulated in Lakes Powell and Mead (table 6). Because so much of the flow increases remained in storage, 35% of the increases evaporated, but hydraulic head in Lakes Powell and Mead was improved considerably. The effect of the increase in hydraulic head on hydropower production more than offset the decrease in hydropower production because less of the runoff increase was released from storage, so that the runoff increase produced 260 kWhs per harvested acre.

Economic Effect of Vegetation Management

The change in timber yield or water use with vegetation treatment, multiplied by the appropriate monetary estimate of the willingness to pay for the change, indicates the economic value of the change. Because the changes predicted here are sufficiently small relative to current production, the marginal values of current production are appropriate estimates of value of the changes in timber yield and water use. Subtracting any costs to bring about the change from the economic values would then yield the net return.

Marginal Values

Returns from initial harvests were assumed to be $135 per Mbf (log scale) at the mill, based on Rocky Mountain Region records (table 7). This return assumed a finished product value of $320 per Mbf minus manufacturing costs of $185 per Mbf. The $320 is a rough average of values that varied from $290 to $350 in the early 1980s.

Managed stands should yield higher values per board foot than the typical harvest of unmanaged stands. We used two different values for managed stands, a value of $169 per Mbf based on the assumption of a 25% increase in value with management, and a value of $225 per Mbf based on a 67% increase in value with management (the latter from BKS).

Ignoring road costs, the present value of the three initial harvests is $15 per acre (discount rate = 0.04). The present values of the precommercial thins and harvests of the regenerated stands are $4 and $8 per acre, depending on whether the lower or higher estimate of value increase with management is used. Thus, the low and high estimates of present value are $11 and $23 per acre, respectively. It is obvious that timber yields alone are insufficient to cover the costs of road construction listed in table 2.

Values for Upper Basin consumptive water uses and Lower Basin agricultural uses are not listed in table 7 because the streamflow increase did not affect the quantity of water in these uses. The high municipal and industrial (M&I) value was computed as the cost of alternative supply to the MWD of approximately $320 per acre-foot in 1982 dollars (from Wahl

Table 7.--Marginal values of timber and water (1982 dollars).[a]

Use	Low	High
Timber yield (per Mbf)[b]		
Initial harvests	135	135
Harvests of managed stands	169	225
Consumptive water use (per acre-foot)		
Lower Basin M&I	60	240
Hydropower (per kWh)	0.018	0.021.0.05[c]
Salt dilution (per mg/l)		
agriculture[d]	$(23{,}900\ e^{0.0052\ TDS})/TDS$	
M&I[e]	242,100[f]	381,000[g]

[a]Adjusted where necessary to 1982 using the GNP implicit price deflator.

[b]Value upon delivery to the mill, log scale.

[c]The exact value used in a given period at a given hydropower plant depended on its plant factor during that period. Larger releases, all else equal, produced a larger plant factor and a smaller unit value.

[d]Source: Anderson and Kleinman (1978). TDS in mg/l. Agricultural damages are assumed to begin at 800 mg/l TDS.

[e]These costs apply to the tds of the water consumed, which is typically lower than the tds of the Colorado River water because of mixing of Colorado River water with other supplies of lower tds.

[f]Source: DOI, cited in Miller et al. (1986).

[g]Source: Kleinman and Brown (1980).

and Davis 1986) minus the cost of pumping Colorado River water through the California Aqueduct ($80 per acre-foot, based on a requirement of 2,000 kWh per acre-foot, from Wahl and Davis 1986), or $240 per acre-foot. The low estimate of $60 per acre-foot is the annualized equivalent, at 4%, of the recent price of Colorado Big Thompson water shares of $1,500 per acre-foot.[4]

Availability of hydropower in a power network typically allows a reduction in power production at the more expensive thermal plants of the network. Thus, hydropower was valued at the cost savings at thermal plants. The low and high estimates of this cost savings differ in the extent to which they attempt to distinguish among the different kinds of thermal plants whose power is replaced when hydropower is available. The low estimate of the value of hydropower assumed, as did BKS, that all hydropower replaced coal – fired power. Coal-fired power was valued at $0.018 per kWh, based on the average fuel costs of coal-fired steam-electric plants (U.S. Department of Energy 1985). The high estimate of the hydropower value assumed that the initial hydropower produced in any given period replaced power otherwise produced by combustion turbine plants, valued at $0.05 per kWh (U.S. Department of Energy 1985), and that additional hydropower replaced coal-fired power valued at $0.018 per kWh. This resulted in a range in unit value of hydropower from $0.021 to $0.05 per kWh depending on the production level at hydropower plants. See the Appendix for more detail on the derivation of the high value estimate.

The values of water in salt dilution reflect the cost that tds impose on water users. The cost to agriculture, from Anderson and Kleinman (1978), is an aggregation of individual cost functions figured for all major Lower Basin (excluding Mexico) agricultural areas relying on Colorado River water (table 7). This cost function, an increasing function of tds, applies only at tds levels above 800 mg/l. The Lower Basin M&I cost of $381,000 per mg/l reflects the discounted cost of reductions in the life of pipes and water using appliances (Kleinman and Brown 1980). Because there is considerable controversy over this cost estimate, a lower estimate of $224,100 per mg/l was also used (table 7). This estimate is an update to 1982 of a 1974 Bureau of Reclamation study, as reported by Miller et al. (1986).

The costs to M&I users were applied over the full range of tds levels, following d'Arge and Eubanks' (1978) report of fluctuating but generally rather consistent costs per mg/l over a range in tds from about 200 to 1,000 mg/l. Also, note that the M&I costs apply to the tds levels of the consumed water, which for the MWD and CAP diversions is a blend of Colorado River water and water from other sources of generally lower tds. The tds levels of the expected blends were estimated for the MWD and CAP, and the appropriate portions of the Lower Basin M&I cost were applied to these blends and to other Lower Basin M&I use areas.[5]

Results

The monetary values were multiplied times the annual quantity of use of the flow increase for each use category over the 72-year simulated period, and the resulting monetary estimates of benefit were discounted to the present. The results of this procedure were then expanded to represent the 120-year period used by BKS to simulate timber yields and management costs.

Economic returns per acre to timber and water yields from intensive vegetation management, ignoring costs of road construction, are listed for the three scenarios in table 8. Returns for Scenario 1 are listed by category, but only the total returns for the other two scenarios are listed. The treatment costs (for sale layout and administration, precommercial thinning, commercial thinning, and final harvest) were subtracted from the at-the-mill timber values to compute the timber returns, although those costs are actually joint costs of

[4]CBT shares sell in the Northern Colorado Water Conservancy District in what is probably the most active water shares market in the US. The price per acre-foot rose above $3,000 in 1980, but has since fallen to about $1,000 (Saliba, et al., in press). We chose $1,500 per acre-foot as a reasonable low end of the price range.

[5]The Lower Basin M&I cost was apportioned as follows: 78% to MWD, 11% to CAP, and 11% to other users along the Colorado River, principally in Las Vegas (d'Arge and Eubanks 1978). Tds of the blended water were estimated from an Environmental Defense Fund (1983) study for MWD and from personal communication with Dennis Sundie, Arizona Department of Water Resources, Phoenix, for the CAP.

Table 8.--Economic returns per acre from vegetation treatments for three scenarios, ignoring road costs (1982 dollars).[a]

	Low value estimates		High value estimates	
	Aver. ann. return	Present value[b]	Aver. ann. return	Present value[b]
Scenario 1 -- Current requests without flexibility in releases[c]				
Timber	0.44	11	0.93	23
Consumptive water use	0.51	13	2.05	51
Hydropower	3.49	87	3.49	87
Salt dilution	0.60	13	0.94	20
Total	5.04	124	7.41	181
Scenario 2 -- Current requests with flexibility in releases[c]				
Total	4.28	105	5.05	124
Scenario 3 -- Future requests with flexibility in releases[c]				
Total	5.74	115	6.55	121

[a]Returns over 120-year time period. Hydrologic results from 72-year simulations extended to 120 years for the purpose of present value computations by assuming mean annual results from the simulations apply to the subsequent 48 years.

[b]Discounted at 4%. Note that present values are sensitive to the timing of the returns, and therefore to the temporal characteristics of the hydrologic trace. The same annual flows in a different order could produce quite different present values.

[c]Flexibility indicates release water from the Mead conservation pool to meet MWD water use requests when that pool is at least 75% full.

timber and water production. Because assignment of joint costs is arbitrary, computation of the relative contribution of timber and water to net return is precluded. However, it is clear that, among the three uses of the additional streamflow, hydropower production contributes more to net return than consumptive use and salt dilution combined. Also, note that the return from hydropower production is the same for both low and high value estimates. The high value estimate yielded a higher estimate of the total value of hydropower production, but not of the value of the increase in production. This is because the streamflow increase was always used for hydropower production when the hydropower plants were producing at a sufficient level of capacity that the additional hydropower replaced only coal-fired thermal power production.

Average annual returns are lowest with Scenario 2, which does not benefit from either consumptive use of the flow increases, as does Scenario 1, or the increased electric energy production of Scenario 3. Assuming the low dollar values, average annual return per acre varies from $4.28 per harvested acre with Scenario 2 to $5.74 with Scenario 3 (table 8). With the high values, average annual return per acre varies from $5.05 with Scenario 2 to $7.41 with Scenario 1.

Discounting the returns at 4 percent, per acre present values over the 120-year time horizon range from $105 to $124 assuming the low value estimates, and from $121 to $181 assuming the high value estimates (table 8). Scenario 1 yields the highest present values for both sets of dollar value estimates. These discounted returns can be compared with the road costs of table 2. Assuming, for example, that 5.5 miles of road are required per square mile of accessed territory and that slopes are moderate, returns from timber and water yields are insufficient to cover road costs with any scenario given the low value estimates. Assuming the high value estimates, however, plus the same road densities and slopes, the returns of Scenario 1 are sufficient to cover costs of intermittent roads; returns of Scenarios 2 and 3 are still insufficient to cover road costs.

Because actual road costs vary significantly with remoteness of the harvest area, and required road type, this particular comparison is of limited practical importance. However, the comparison does point out the significant sensitivity of the results to the values assumed and to reservoir management flexibility.

Qualifications

The qualifications on use of this analysis include (1) reminders of what the analysis did not attempt to contribute to the decision regarding vegetation treatment, and (2) major assumptions upon which the analysis is based, that perhaps biased the results.

The analysis did not attempt to measure the effect of the roads and vegetation treatments on wildlife populations, or on scenic quality and recreation use, at treatment sites or along water courses and impoundments. Concern for such effects should be included in any complete analysis of the treatments. In addition to such omissions, it is worth mentioning that the analysis is limited in that it did not examine other alternatives for (1) increasing timber products or substitutes for timber products or (2) increasing water yield or otherwise dealing with the expected water shortage. Even if the benefits of a vegetation treatment regime were shown to be greater than the costs, there may be some more efficient approach to the same goals.

The model upon which the analysis of water storage and routing is based is a major simplification of a very complex situation. Because of this simplification, the analysis is preliminary. The most important assumptions of the analysis include the following: (1) Aggregation over space. The aggregation of consumptive use requests into just a few use locations for modeling may have masked localized uses that could have been assisted by the flow increases. (2) Aggregation over time. The aggregation over time to four time periods per year may have caused inaccuracies, for example, in computations of head for estimating power production from flow through the turbines, or of tds of stored water. (3) Flows. The analysis assumed that the 72-year period from 1906-1977 is a valid representation of pretreatment flows to be expected in the future (see BHL for some sensitivity analysis of this assumption), and that annual flow increases would be proportional to nearby annual mainstem flow. These assumptions may not hold. (4) Institutions. Current water allocation institutions

were assumed to remain unchanged. Institutional changes could significantly alter the disposition of both preincrease flows and flow increases (e.g., see BHL on the effect of allocating water by marginal economic value). (5) Salt concentrations. Salt (tds) loading and salt mixing within reservoirs were modeled in a simplistic way. Recent and ongoing research should be incorporated into a more complete analysis.[6] (6) Monetary values. Future real prices, especially fuel prices used to value hydroelectric energy, may be substantially different from recent ones. (7) Linearity. It was assumed that the hydrologic results from harvest of 334,600 acres apply to any subset of this area.

Conclusions

Modeling river basin water storage, loss, and routing is important in order to understand the disposition of streamflow increases. The timing of such increases, as well as the facilities and institutions that control their allocation, can play important roles in consumptive use of the increase. In the Colorado River Basin, it appears that--given current facilities and institutions--the flow increases would be largely unused consumptively.

Uses of the flow increases in both power production and salt dilution contributed in large measure to the total return of the vegetation treatment. While the value of instream uses will not outweigh the value of consumptive uses in all locations, instream uses should probably receive increased emphasis.

The economic results are largely indeterminant because of the sensitivity of net returns to the values assumed for water yields and the road construction requirements. Both the low and high value estimates used in this study are plausible given current knowledge. If watershed management decisions are to be analyzed from an economic efficiency perspective in the future, research is needed to more accurately estimate the values.

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[6]Current research by BHL is intended to improve upon the earlier analysis by disaggregating both the space and time aspects of the model, and by simulating the variation in salt loading with variation in pretreatment flow and water withdrawl.

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Appendix

Hydropower

For each period, energy production in kilowatt hours (kWh) was computed as:

$$kWh_{ij} = H_{ij} * F_{ij} * Ef_j * C \quad [1]$$

subject to

$$H_j \geq Hm_j \quad [2]$$

$$kWh_{ij} \leq M_{ij} \quad [3]$$

where

I		signifies time period
J		signifies hydroelectric dam
H	=	head in feet
F	=	flow in acre-feet
Ef	=	efficiency
Hm	=	minimum head for intake
M	=	maximum productive capacity (a function of turbine and generator capacities)
C	=	1.0253, a constant necessary to convert from acre – feet of flow to kWh (see Creager and Justin 1950).

Because hydropower plants can be brought on and off line easily, they are used when possible to replace power from the relatively expensive combustion turbine plants that supply additional power needed during peak demand times of the day. However, depending on power plant capacity and water releases from the dam, hydropower plants may run more continuously, thereby replacing baseload power typically produced by coal-fired plants.

The exact proportion of total power production at a hydropower plant that replaces power from combustion turbine plants depends on the proportion of the time that the hydropower plant is producing power (its production as a proportion of its capacity, or plant factor) and on how that power can be incorporated into the total power network. Information from the Western Area Power Administration suggests that a hydropower plant in the Colorado River Basin with a plant factor of 0.1 or less typically replaces only combination turbine power and that at greater plant factors coal-fired power is also replaced.

The high estimate of the hydropower value assumed that the value of the power was a function of the plant factor. For plant factors of less than or equal to 0.1, hydropower was assumed to replace power otherwise produced by combustion

turbine plants, and was valued at $0.05 per kWh. For plant factors greater than 0.1, it was assumed that the hydropower associated with the 0.1 plant factor continued to replace combustion turbine power valued at $0.05 per kWh, and that any additional hydropower replaced coal-fired power valued at $0.018 per kWh, using the following weighted average computation:

$$\text{cost savings per kWh} = [(0.1*0.05) + (PF-0.1)*0.018]/PF \quad [4]$$

where PF indicates plant factor.

Total Dissolved Solids

The following relationships were used for total dissolved solid computations:

$$LBTDS_i = C * (RS_i + LBS_i) / (RW_i + LBIF_i) \quad [5]$$

where

$$RS_i = RW_i * STDS_i / C \quad [6]$$

$$STDS_i = C * (SS_{i-1} + UBS_i) / (SW_{i-1} + UBIF_i - E_i) \quad [7]$$

$$SS_i = SS_{i-1} + UBS_i - RS_i \quad [8]$$

$$SW_i = SW_{i-1} + UBIF_i - E_i - RW_i \quad [9]$$

given

$LBTDS_i$ = Lower Basin tds in period i (mg/l)

$STDS_i$ = tds of water stored in Powell and Mead in period i (mg/l)

RS_i = salt mass released from Mead reservoir in period i (tons)

RW_i = water released from Mead in period i (acre-feet)

LBS_i = salt mass entering Colorado River below Mead in period i (tons)

UBS_i = salt mass entering the Colorado River above Mead in period i (tons)

$LBIF_i$ = water inflow below Mead in period i (acre-feet)

$UBIF_i$ = water inflow to Powell plus inflow between Powell and Mead in period i (acre-feet)

SS_{i-1} = salt mass in storage in Powell and Mead at end of period i-1, beginning of period i (tons)

SW_{i-1} = water in storage in Powell and Mead at end of period i-1, beginning of period i (tons)

E_i = evaporation from Powell and Mead reservoirs in period i (acre-feet)

C = 735.374, a constant to convert from tons/acre – foot to mg/l.

Poster Papers

Krummholz Snowdrifts: Hydrologic Implications at a Colorado Treeline Site

Neil H. Berg[1]

Abstract--The water equivalent of snow contained in drifts downwind of krummholz vegetation at treeline on Niwot Ridge in the Colorado Front Range is estimated at 8,060 m^3 annually (1830 m^3 km^{-2} land area), or about 1% of the summer streamflow from a 191-ha alpine basin adjacent to Niwot Ridge. Most of this water would be lost to sublimation if the vegetation did not capture the snow. Much of the water becomes available after the date of peak discharge and contributes to late-season water supply and soil water recharge.

Blowing and drifting snow are important factors in alpine environments. The upper reaches of the subalpine zone become a deposition site for snow redistributed from the alpine. At the forest-alpine tundra ecotone, low-lying "krummholz" vegetation is the first impediment to snow-bearing winds. When snow is redistributed into drifts to the lee of krummholz tree islands, evaporation of wind-driven snow is reduced. As snow drifts melt, they become water sources to natural ecosystems and, particularly in their late-season residence after the primary snow cover has melted, for human use.

Niwot Ridge, an east-west trending spur on the east slope of the Colorado Front Range, 35 km northwest of Boulder, Colorado (40o3'20" N, 105o35' W), ranges in elevation from 3450 to 3800 m msl. At increasing elevations on Niwot Ridge, the closed crown forest gives way to stunted growth forms near the upper limit of tree growth as environmental conditions increase in severity. Severely deformed "krummholz" exist as isolated clumps of one or more trees. "Flag" krummholz grow where environmental conditions allow one or several vertical branches to survive above the protection of the winter snowpack; below the pack, growth is dense and mat-like. "Mat" krummholz exist at slightly higher elevations under extreme conditions that do not allow survival of the vertical leaders (Daly 1984). On Niwot Ridge *Picea engelmannii* (Engelmann spruce), with admixtures of *Abies lasiocarpa* (subalpine fir) and *Pinus flexilis* (limber pine), are the primary mat krummholz species. Krummholz occur over an elevation range of approximately 200 m and form a discontinuous catchment zone for blowing snow spanning the length of the Front Range (Ives and Hansen-Bristow 1983). This paper investigates the hydrologic role of krummholz snowdrifts and estimates the water equivalence and timing of release of snowmelt water from krummholz drifts on Niwot Ridge.

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Methods

To estimate the water equivalent of krummholz snow drifts, four steps were followed: (1) measure krummholz and drift geometries; (2) relate krummholz geometry to drift shape to determine individual snowdrift volumes; (3) quantify krummholz occurrence on Niwot Ridge; and (4) determine water equivalent.

Mat krummholz tend to be wedge-shaped with their apex height at the downwind edge (fig. 1). Width and height measurements were made at the apex of 171 randomly-selected mat krummholz during February and March, 1975, near the central portion of the Ridge. The length of the associated lee drifts and snow depth at the apex were also recorded. Techniques have been established to estimate drift volume, V. Tabler (1975:95) developed a snow retention model for sagebrush (Artemisia spp.) in which the drift forming behind an isolated plant approximates the shape of a half-cone, with length 10H (H= plant height), so that $V = 5.2H^3$.

The areal frequency of mat krummholz was determined by relating aerial photograph observations to a vegetation map of the Niwot Ridge forest-alpine tundra ecotone. Hansen-Bristow's (1981) vegetation map (1:10,000 scale) shows mat krummholz in a discontinuous band approximately 350 m wide over an area about 4.4 km^2 along the eastern two-thirds of Niwot Ridge. Since individual plants were not designated on this map, color aerial photographs (circa 1:15,000 scale) taken October 2, 1974 were analyzed with a zoom stereoscope capable of 10 X magnification. Individual trees were identified

Figure 1.--Schematic representation of a mat krummholz and lee snowdrift.

on the photograph and compared to their location on the map to determine growth form. Shadow length helped identify flagged trees.

Determination of snow water equivalent requires knowledge of the density of the drifts. Koerner (1969) found density in krummholz lee drifts on Niwot Ridge to vary generally between 0.40 g cm^{-3} and 0.47 g cm^{-3} and increase through time into the ablation period. These measurements, based on approximately 100 sampling points, are the basis for use of 0.45 g cm^{-3} as the value for snow density at the maximum accumulation date. Water equivalent for individual snow drifts follows as the product of krummholz frequency, drift volume, and density. Total snow drift water equivalent for the basin is calculated by applying a probability density function developed from the field measurements of apex snow depth (taken to equal H) to the total krummholz population on the Ridge by means of the "half-cone" volume equation.

Results and Discussion

Measured tree heights (table 1) were within the ranges (0.5 to 2 m) measured by Koerner (1969), and noted by Hansen-Bristow (1981:38): "In this form the tree is dwarfed to a mat, usually no higher than 1.5 m, but up to 5 m long." Similarly, tree

Table 1.--Krummholz and lee snowdrift dimensions on Niwot Ridge, Colorado, February-March, 1975.

Variable	Mean (cm)	Median (cm)	S.D. (cm)	Max. (cm)	Min. (cm)	Sample size
Krummholz width	269	255	123	755	55	170
Krummholz height at apex	112	115	45	295	12	131
Krummholz length	375	320	245	2,000	60	171
Drift length	605	560	282	1,750	100	171
Drift depth at krummholz apex	76	75	34	168	8	171

island lengths (table 1), averaging 3.75 m, were similar to those mapped by Koerner (1969). Mean tree width-to-height ratio was 2.4, and lee drift lengths averaged 8 times maximum drift depth (table 1). Relative variation of tree length was greater than for the other measured properties. The coefficient of variation ranged from 0.40 to 0.47 for the other four variables, but was 0.65 for tree length. The distribution of snow depths at the tree apex is not significantly different from normal (alpha = 0.05) (fig. 2).

Four thousand, six hundred and ninety mat krummholz (approximately 670 km^{-2}) were estimated as occurring within the Niwot Ridge forest-alpine tundra ecotone. The volume of snow in the associated lee drifts was estimated at 17900 m3, with a snow water equivalent of 8,060 m^3, or 1,830 m^3 km^{-2} (at snow density = 0.45 g cm^{-3}). To put this value into perspective, in 1974, a slightly above-average winter precipitation year on Niwot Ridge, peak daily discharge from a 191-ha alpine basin immediately south of the Ridge was 35,200 m^3 (Carroll 1974). Drift snow water equivalent therefore approximated one-quarter of the peak annual single-day streamflow, or about 0.8% of the mid-June through late-October streamflow.

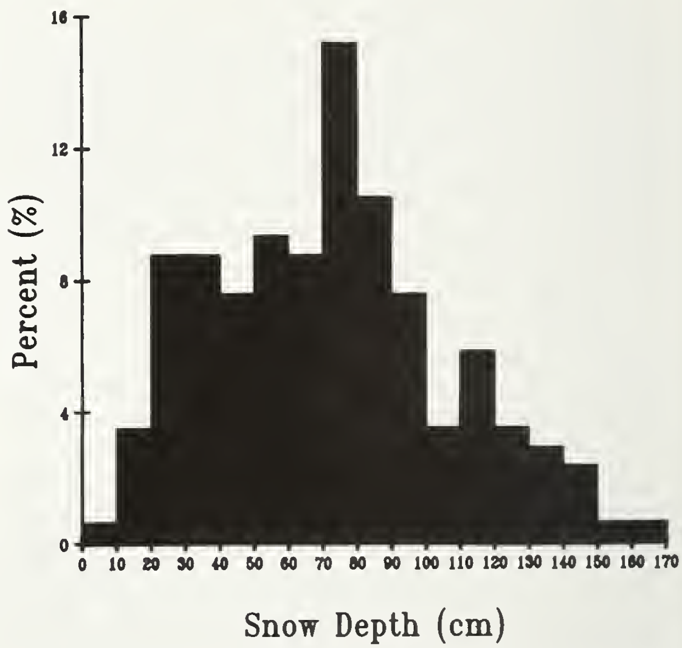

Figure 2.--Krummholz apex snow depths on Niwot Ridge, Colorado.

Error Assessment

The magnitude of errors associated with several components of this analysis needs explanation. Errors associated with the krummholz frequency estimate are probably the largest in this study. Even with the optical magnification available for the aerial photograph interpretation, trees less than 20 cm tall may not have been identified and the distinction between mat and flagged forms was not always completely reliable.

The half-cone equation (Tabler 1975) was formulated for an area with unidirectional winds, uniform terrain sloping less than 15%, sufficient snow for the drifts to reach equilibrium profiles, crown width approximately twice crown height, and drifts approximately 10H in length. These conditions were generally satisfied within the krummholz communities sampled on Niwot Ridge. In this application, apex snow depth is the effective crown height, since the top portion of the krummholz is sparsely foliated and relatively ineffectual as an aerodynamic barrier. On the average, measured tree width was slightly more than twice tree height and drift length was slightly less than 10 times snow depth at the apex. The importance of barrier height in determining lee drift volume is supported by numerous snow fence studies (Tabler 1986) and by the moderately high Pearson correlation coefficients for associations between drift length (a proxy for drift volume) and both krummholz height ($r= 0.82$) and apex snow depth ($r= 0.78$). The shape and porosity of krummholz and sagebrush differ; krummholz are wedge-shaped whereas sagebrush are spherical. Not enough is known about the magnitude of these variations to quantify the error.

Use of a constant value for snow density is a simplification. Snow deposited in the interstices of the vegetative mat, while relatively low in volume, is not accommodated, nor is the interaction between krummholz drifts and topographic snow traps. Snow firnification, drift erosion due to high velocity winds, variations in tree island aspect and the consequent variations in ablation rates due to differences in insolation are likewise not considered. These influences are essentially impossible to quantify on a basin scale. The calculations described here are a conservative "first approximation" of drift snow water equivalent.

Timing of Water Availability

Even if the actual water equivalent is twice the estimated amount, the total water contained in the drifts is relatively small when compared to typical streamflow volumes. The importance of this water is not primarily in its magnitude, but may be in the timing of its availability.

Estimation of the timing of water release from the drifts on Niwot Ridge has relied on two data sources: field measurements of several mat krummholz lee drifts made throughout the 1965 ablation period (Koerner 1969), and of a flag krummholz and terrain drifts during 1974 (Berg 1977).

Extrapolation of Koerner's data suggested drift disappearance by June 25, 1965. Extreme snowpack ablation rates occurred in 1965 (Rennick 1966), therefore the late-June meltout date was probably earlier than average. Even so, in an above-normal snowfall year, 1974, peak stream discharge occurred on June 24, suggesting that krummholz drifts may melt out after the stream flow peak. Casual observations over several years by Daly (per. comm. 1987) suggest, however, that mat krummholz drifts melt relatively quickly, and disappear probably only a few days after the date of peak stream discharge. This may be due to their relatively shallow depths. Drifts behind flag krummholz, on the other hand, can persist several weeks longer, often well into July. The 1974 measurements support this claim. Maximum depths at terrain drifts were greater than 3.8 m on April 17, 1974, a date when the maximum depth recorded at a nearby flag krummholz drift was 3.7 m. Snow over 1.5 m deep persisted at the terrain drifts as late as mid-July 1974, several weeks after the June 24 peak streamflow discharge in nearby Green Lakes Valley. Although measurements of the flag krummholz drift were not made in July, given the near equality of snow depths on April 17, it is reasonable to hypothesize that the flag krummholz drift had not completely melted in mid-July, 1974. The flag form of krummholz is generally larger than the mat form, so that deeper drifts form which take longer to melt. It may be that the optimal condition for both drift accumulation and melt delay occurs when krummholz, either flag or mat, are situated immediately upwind of terrain snow traps, as on ridge-terrace lines (Koerner 1969).

Alpine snowfields generally supply late season runoff to lowland areas, and the preliminary observations reported in this paper suggest that drifts associated with krummholz contribute to runoff even later than the average from alpine catchments. Although the quantity of water from the drifts is relatively small, about 1% of the summer streamflow from a 191-ha alpine basin adjacent to the study area (or one-quarter of the peak single day discharge), a 7-to-10 day delay in release of snowmelt water from the larger krummholz drifts adds to the importance of this water source in an otherwise "summer dry" lowland environment. Much of this water would be lost to sublimation if the vegetation did not accumulate snowdrifts.

Acknowledgements

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The Coon Creek Water Yield Augmentation Pilot Project

G. S. Bevenger and C. A. Troendle[1]

Abstract--Research in the Rocky Mountain subalpine zone has demonstrated that vegetative manipulation (primarily clearcutting) causes a net reduction in evapotranspirational losses, changes the aerodynamics and energy balance of the timber stand, and results in increased streamflow. Because the results of research on small watersheds has shown that water yield can be increased, and because forest management represents one of several options for manipulating water yield, the Coon Creek Water Yield Augmentation Pilot Project was initiated. The objective of the project is to apply state-of-the-art technology in water yield management on an operational timber sale. The project also will make possible large-scale testing and field verification of hydrologic prediction tools so commonly used in planning.

More than 70 years of watershed research throughout the United States, and specifically in the West, has provided the technology to substantially increase usable water from forested lands. The long-term intent of the Coon Creek project is to produce increased quantities of usable water in harmony with sound multiresource management of National Forest land. The Forest Service, Rocky Mountain Region, responded to a 1980 national initiative to augment water yield by proposing the Coon Creek Pilot Project to apply technology developed primarily at the Fraser Experimental Forest and elsewhere in the Rocky Mountain Region. A second objective is to evaluate, on a large scale, the reliability of state-of-the-art hydrologic predictive tools currently being used, such as the Subalpine Water Balance Model (Leaf and Brink 1973a, 1973b), WRENSS (Troendle and Leaf 1980a), and other locally developed models.

Coon Creek was selected as the project area primarily because the watershed in which it is located, the East Fork of the Encampment River, is a large, uncut and unroaded watershed of the size necessary for evaluating a commercially viable timber sale. The basin consists of two watersheds of comparable size, aspect, and timber types, which allows for a paired watershed study. The drainages are uniformly covered with commercially operable timber, and the drainage selected for treatment (Coon Creek) can be logged by conventional harvesting methods using standard silvicultural practices (patch clearcutting).

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Watershed Description

Coon Creek, the treatment watershed, is a 3,987-acre drainage located on the Hayden District of the Medicine Bow National Forest in Wyoming. It drains to the west at elevations ranging from 8,800 to 10,980 feet. Adjacent to Coon Creek is the Upper East Fork, the 2,252-acre control watershed. The Upper East Fork drains to the southwest at elevations ranging from 8,800 to 10,090 feet. Soils in both drainages are developing from alluvium and colluvium by weathering of igneous and metamorphic material. Soils generally vary between 20 and 60 inches in depth and are well drained. The soils are capable of absorbing water at rates in excess of snowmelt and normal rainfall intensities, so surface erosion is minimal.

The climate of the area is generally influenced by frontal systems and orographic storms during winter months, and by orographic and convectional storms during summer months. Mean yearly precipitation and mean yearly temperatures are estimated to be 40 inches and 34° F, respectively. Approximately 70% of the precipitation comes in the form of snow. Streamflow from May to September is directly and indirectly the result of snowmelt, and flow generation is mostly subsurface in nature. Estimated average annual water yield is 1.8 acre-feet per acre, with water quality generally good to excellent.

Forest cover consists of spruce-fir stands along stream courses, on north slopes, and at upper slope positions. Lodgepole pine grows on all low- and mid-elevation southerly or high-energy exposures. Alpine tundra is above timberline. Part of the area was extensively harvested for railroad ties in the early 1900s, but regrowth now completely occupies the site hydrologically.

Treatment and Measurement Methods

In 1982, 8-foot Cipoletti weirs were built on both East Fork and Coon Creek, and they are operated from April to October each year. To further assist the calibration process and to evaluate treatment effects, an extensive network of climatic instrumentation also was installed across the two watersheds in 1982 and 1983 (fig. 1). Climatic parameters being monitored include solar radiation, air temperature, relative humidity, and precipitation. Precipitation measurements include both rain and snow components. Included in the snow component measurement is a 600-point, random-walk snowcourse, which is surveyed around April 1 of each year. Survey data are used to estimate mean water equivalent in the snowpack for each watershed (all instrumentation and snowcourse locations are shown in fig. 1).

To date, 4 to 5 years of record have been collected, depending on the parameter: 4 years of flow record (1987 is the fifth year), 5 years of snowcourse record, and 4 years of temperature, precipitation, radiation, and humidity data. So far, the correlations between the watersheds appear quite good for all parameters.

Watershed Calibration

Average monthly precipitation is fairly well distributed throughout the year on both watersheds (fig. 2). Rain falls during the months of June through August, while snowfall dominates from September to May. There is a strong orographic effect between elevation and precipitation on Coon Creek, as is indexed by the relationship shown in figure 3. The orographic effect holds year round.

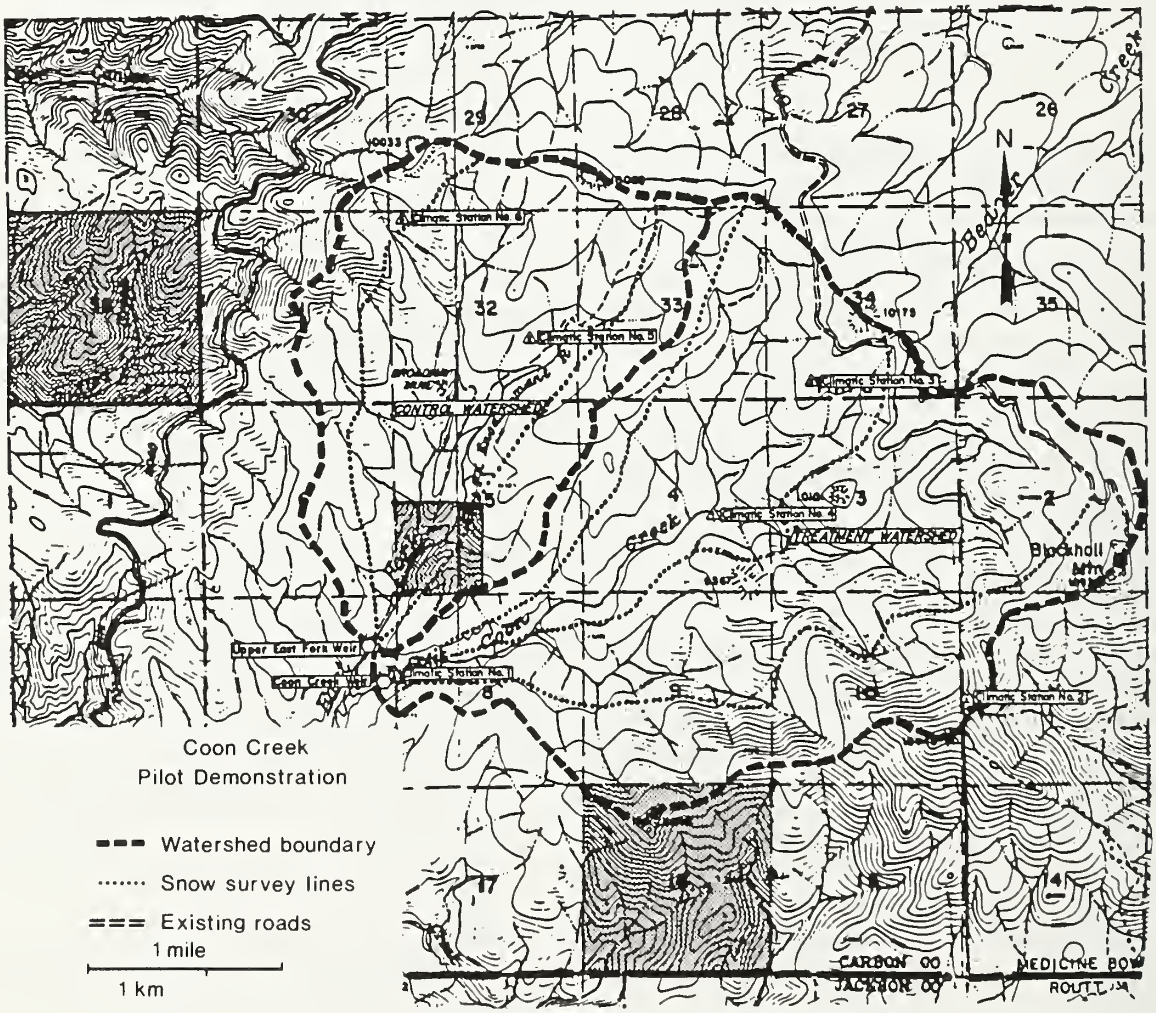

Figure 1.--Map of the Coon Creek and East Fork watersheds showing snow course, climatic station, and streamgage locations.

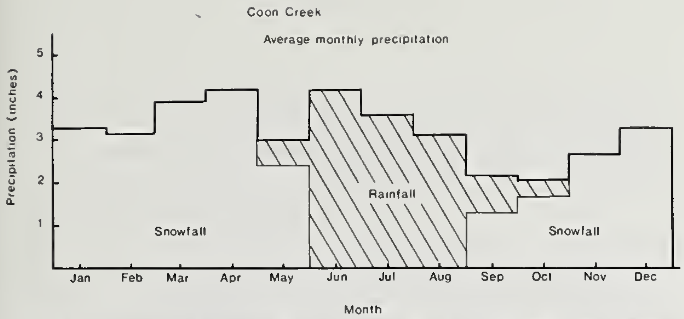

Figure 2.--Average monthly precipitation for the Coon Creek watershed.

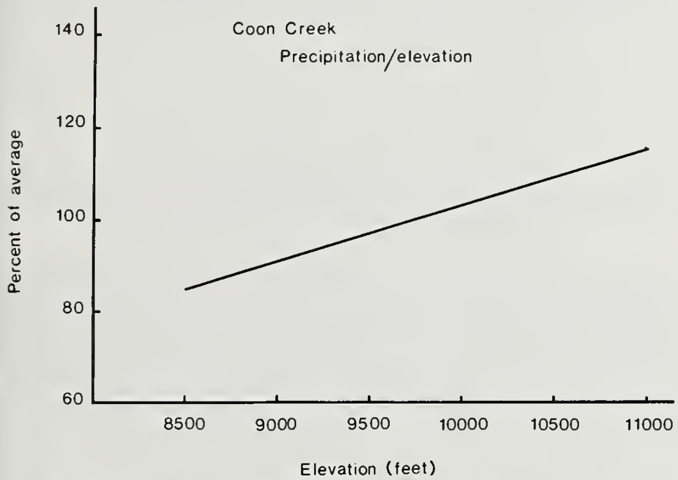

Figure 3.--Adjustment factor to be used to adjust average monthly watershed precipitation (fig. 2) for elevational effect.

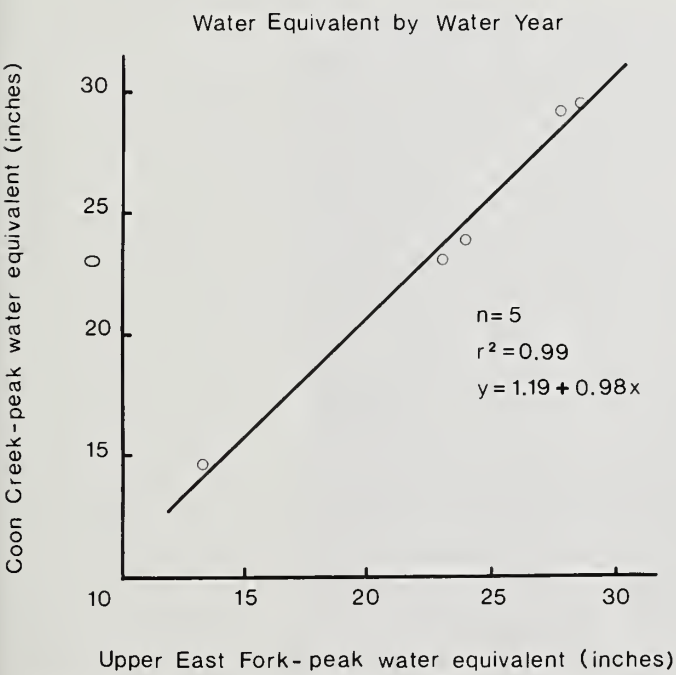

Figure 4.--The relationship between peak water equivalent on the Coon Creek and East Fork watersheds.

In addition to the climatic installations, permanently marked random walk snowcourses also are located in each watershed. Approximately 200 stations are located in the East Fork drainage and 400 in the Coon Creek drainage (fig. 1). Although the 5 years of existing data demonstrate considerable variability among stations, snowpack accumulation increases significantly with elevation on all snowcourse transects. Figure 4 presents the relationship of mean peak water equivalent on the East Fork and Coon Creek watersheds. The agreement is quite strong: an r^2 of 0.99 with a standard error of 0.38 inch. Water equivalent on Coon Creek ranged from 15 to 30 inches during the 5 years of record, or from two-thirds of normal to a one in 40-year extreme.

The average annual hydrographs for Upper East Fork and Coon Creek for the years 1983 to 1986 show a strong correlation (fig. 5). The majority of flow occurs in May and June, and is the result of melting snowpack. Analysis of the first 4 years of record indicates that 83% of the variation in flow from Coon Creek and 95% of the variation on East Fork can be explained by mean peak water equivalent (PWE) in the snowpack on April 1 (fig. 4). Although the correlations are higher than usually observed elsewhere, the relationship is typical of that for the subalpine forest (Troendle and Leaf 1980; Troendle and King 1985, 1987).

The correlation between annual flows from Upper East Fork and Coon Creek, like peak water equivalent, also is quite good (fig. 6). The first 4 years of record were very wet years, with flow level very high and having very little variation from year to year. However, 1987 appears to be a dry year (60% of normal), and the estimated flow level is quite low (estimate is measured flow for April, May, and June for both watersheds). This low value provides the range needed in order to have confidence in the application of the calibration relationship. The range in return intervals for the calibration period (5 years) goes from one in 0.60 year to one in 40 years.

In addition to annual flow, we also evaluated the character and relationship of storm discharge from the two watersheds. Thirty-one storms (rain only) occurred during the months of July through September of 1983 and 1984. Only a minimal portion of the precipitation was returned as stormflow or quickflow (using definition of Hewlett and Hibbert 1967). The individual rainfall events ranged from 0.01 to 0.78 inch, while stormflow response varied from 0.001 to 0.019 inch. The average storm size was 0.31 inch, while the average response was 0.01 inch, or 3% of the precipitation returned as flow. Subsequent analysis indicated no correlation ($r^2 = 0.00002$) between storm size and storm response. The lack of response is not surprising, since summer precipitation does not appear to be well correlated with flow in the subalpine environment (Troendle and Leaf 1980; Troendle and King 1985, 1987). What storm response that did occur probably was the result of direct channel interception of the precipitation.

The 5 years of record currently available indicate that precipitation, snowpack accumulation, and flow all are well correlated between the watersheds, and the proposed harvest

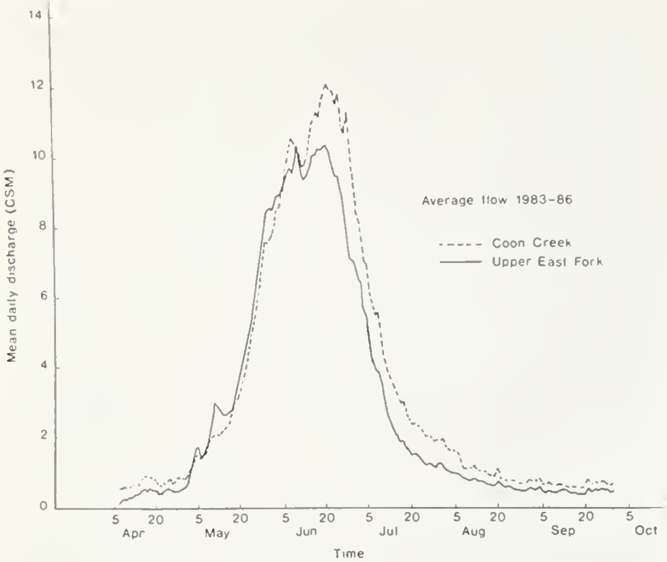

Figure 5.--Average annual hydrographs (1983 to 1986) for Coon Creek and Upper East Fork drainages.

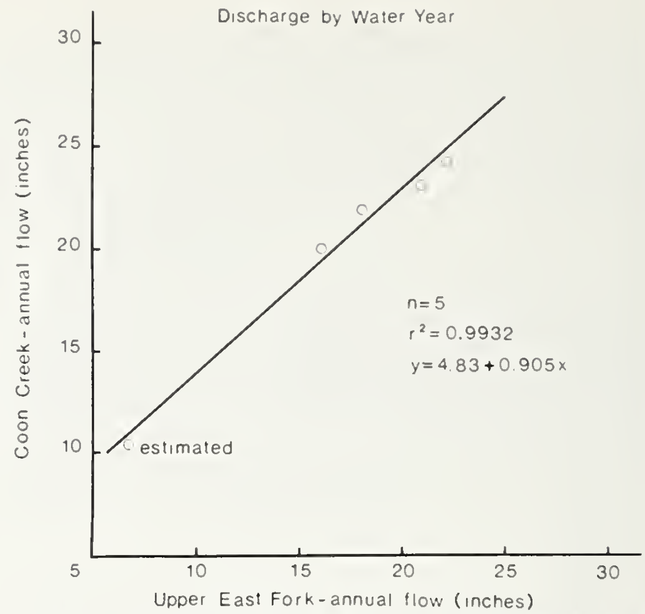

Figure 6.--The relationship between flow on Coon Creek and Upper East Fork for the first 5 years of calibration.

can proceed as planned, beginning in 1989. We anticipate a several-inch increase in flow, but a change as small as 1 inch will be detectable.

Approximately 27% of the Coon Creek watershed will be harvested in small irregular clearcuts ranging in size from a few acres to 13 acres (fig. 7). No riparian areas will be harvested, and the proposed practice will meet all requirements of the existing forest plan. Current plans are to monitor the watershed for several years following harvest to determine the response, and how accurately we were able to predict it.

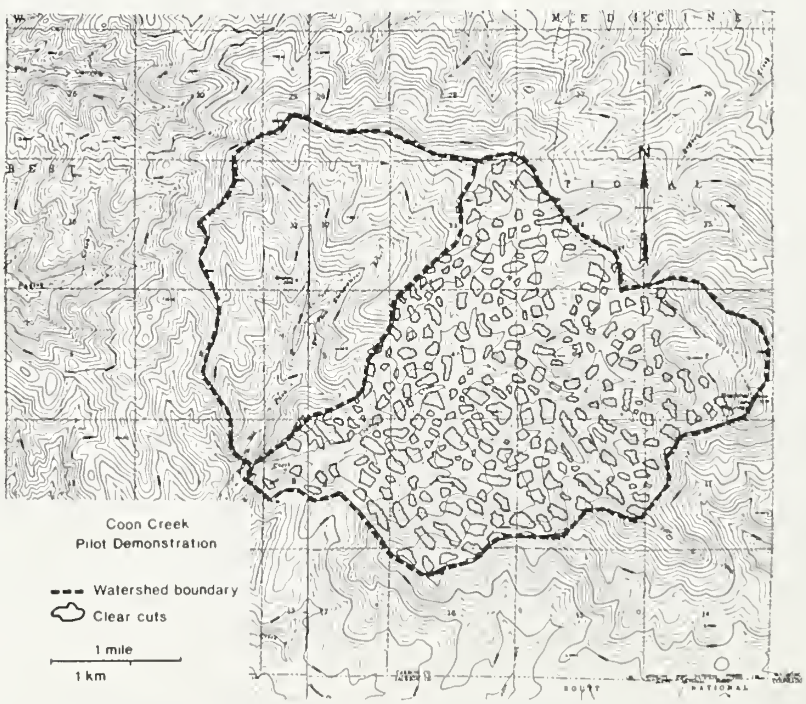

Figure 7.--Proposed sale layout, Coon Creek watershed.

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2H5

Studies on the Resting Site Ecology of Marten in the Central Rocky Mountains

Steven W. Buskirk, Henry J. Harlow, and Steven C. Forrest[1]

Abstract--Studies on the resting site ecology of marten *(Martes americana)* in the central Rocky Mountains are described. Body temperature dynamics, ambient temperature-specific metabolic rates, ecological characteristics of resting sites and the relationship between resting site use and environmental factors are being studied. These studies will provide insight into the basis for the old-growth association of marten.

The marten *(Martes americana)* has been selected as a management indicator species by several national forests of the intermountain West. One ecological trait makes this designation particularly appropriate; marten are among the most habitat-specialized of North American mammals (fig. 1), being largely restricted to conifer-dominated forests and attaining their highest densities in late successional stands (Allen 1984). Harris (1984) considered marten to be among the most climax-dependent of North American forest mammals.

What are the bases of the old-growth dependency of marten? Do marten require old-growth because of the types of prey that are found there, because of favorable access to prey, because of the availability of predator-avoidance habitats to marten themselves, or because of the availability of features that are important as thermal cover? Our studies are directed at understanding how marten may use specific forest habitat features to thermoregulate in winter.

A number of resting sites used by free-ranging marten have been described (table 1). These sites range from the forest canopy to beneath the soil surface. Particularly in winter, resting sites are often associated with coarse woody debris, including logs and stumps, below the snow surface (Spencer 1981, Steventon and Major 1982, Martin and Barrett 1983). In summer, marten usually rest in sites above the soil surface, often in the canopy layer (Burnett 1981, Martin and Barrett 1983). However, it is not clear whether these sites were selected on the basis of convenience, or other factors. It is an objective of our studies to monitor physiological and microenvironmental in order to help discern this relationship.

Although several mustelid species have received attention from physiologists because of their long, thin shapes and consequently high surface area/mass ratios (e.g. Brown and Lasiewski 1972, Iverson 1972), few metabolic or energetic studies of marten have been undertaken. Worthen and Kilgore (1981) found that the lower critical temperature (T_{lc}, the ambient temperature [T_a] below which an animal must shiver to maintain its body core temperature [T_b]) of marten was 29° C, which is higher than the T_a experienced by free-ranging marten for most, if not all of the year. In an associated study on metabolic responses by marten to low T_as, we reinvestigated this relationship and calculated a considerably lower value of T_{lc} of 16° C. Even with this lower (and more adaptive) value, the thermal relationship of the marten to its environment is a tenuous one. During winter, when marten must maintain T_b-T_a gradients of up to 80° C, and T_as are 11-57° C below our calculated T_{lc}, energetic costs of foraging and of resting above the snow surface must be very high. These postulated energy losses caused us to suspect that marten would be highly selective in their choice of resting sites during winter, and would exhibit patterns of resting site use that were keyed to weather variables.

Study Area and Methods

Field studies have been carried out in the Snowy Range region of the Medicine Bow National Forest, in southeastern Wyoming. The approximately 108-km^2 study area ranges from 2,500 m to 3,300 m in elevation and includes two forest zones, one dominated by Engelmann spruce *(Picea engelmannii)* and subalpine fir *(Abies lasiocarpa)*, the other by lodgepole pine *(Pinus contorta)*. Spruce-fir stands contain large, old trees, hold large amounts of large dead woody material, are uneven-aged and generally meet criteria (Franklin et al. 1981) for old-growth forest. The area is used intensively for recreation, with

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Table 1. Resting sites reported to be used by American marten, by type.

CITATION AND SEASON OF STUDY[1]	Study Location	RESTING SITE CATEGORY																			Total
		Sites > 2m Above Ground						Sites < 2m Above Ground													
		Canopy Layer				Coarse Woody Debris							Other								
		Crown	Limb or branch	Witches broom/dwarf mistletoe	Squirrel nest	Top of broken snag	High tree/snag cavity	Low tree/snag cavity	In or under stump	Inside downed log	Under downed log	Slash pile	Talus or rock pile	Squirrel midden	Animal burrow	Animal surface nest	Man-made structure	Unknown surface (subnivean)	Other		
Burnett (1981)	MT																				
Spring, Summer, Fall			11		2		3	1				1					1		1		20
Winter			8	1	2							4			1						16
Buskirk (1984)	AK																				
Spring, Summer, Fall																					
Winter					3									28	6						37
Campbell (1979)	WY																				
Spring, Summer, Fall				5			14					4									23
Winter																					
Hargis and McCullough (1984)	CA																				
Spring, Summer, Fall																					
Winter											2						1				3
Hauptman (1979)	WY																				
Spring, Summer, Fall				1			8/7[2]			2[2]			1								12
Winter											16										16
Marshall (1942)	ID																				
Spring, Summer, Fall																					
Winter							1		2		13										16
Martin and Barrett (1983)	CA																				
Spring, Summer, Fall		16				21		3	46		19		1						18		124
Winter		6					36	3	5		41		2					24			117
Masters (1980)	NY																				
Spring, Summer, Fall			3				1	1													5
Winter																					
Mech and Rogers (1977)	MN																				
Spring, Summer, Fall			1										4	2							7
Winter													2		3						5
Newby (1951)	WA																				
Spring, Summer, Fall																					
Winter							X		X			X									
Simon (1980)	CA																				
Spring, Summer, Fall		5	1			26		1[2]										3			36
Winter																					
Spencer (1981)	CA																				
Spring, Summer, Fall		4	8	6		3	12	4	5		3		3			4					52
Winter								7	7		13	6	2			1	7				43
Spencer (In press)	WA																				
Spring, Summer, Fall																					
Winter															2			9			11
Steventon and Major (1982)	ME																				
Spring, Summer, Fall																					
Winter		1						2	19			3									25
Wynne and Sherburne (1984)	ME																				
Spring, Summer, Fall		6/2[2]		18		3/2[2]	4[2]												8		39
Winter																					

[1] Spring, Summer, Fall considered snow free. Daytime temperatures generally over 0° C.

[2] Natal (maternal) den.

X Occurs in category.

about 140 summer cabins and a public ski area. More detailed descriptions of the study area are provided by Oosting and Reed (1952), Billings (1969), and Fahey (1983).

Marten were captured in baited live traps using oil of anise as a lure. Traps were placed in protected sites and were provided with floors of closed-cell polyurethane foam. Trapping was conducted for periods of 2-10 nights on an intermittent basis from November 1985 to February 1986 and from November 1986 to January 1987. The total effort involved 496 trap-nights at an estimated density of 1.8 traps/km snowmobile trail. No injury or mortality to marten resulted from trapping operations. Captured animals were transported to the University of Wyoming. Under ketamine hydrochloride anesthesia, a precalibrated $\underline{T}_b$-sensitive transmitter (Minimitter Model L) was surgically inserted into the peritoneal cavity and sutured to the midventral abdominal wall. A radiocollar (AVM Instrument Co.) was affixed to each animal. After recovery, each animal was released at the capture site.

Radio tracking has been conducted by snowmachine and on foot during daylight hours. When marten have been found resting, the resting site has been marked and a recording device left within 15 m of the site to sample and record transmissions from the radio implants. Each recording device consists of a transistor receiver with crystals matched to the frequencies of the temperature implants, a solid state timing device with controls for setting the duration of the signals recorded and the intervals between between readings, and an inexpensive cassette tape deck, all powered by cold resistant lithium batteries. Tapes of transmitted clicks have been converted to T_b manually using calibration curves. Standard weather data was recorded by four climate stations within the study area. In addition, temperature data were gathered for 7 sites above and within the snow layer of an old-growth spruce-fir stand.

Results

Body temperature dynamics, patterns of resting site use and activity patterns of eight marten (six males, two females) were studied over two winter field seasons. No radio collars and only two temperature implants failed prematurely. Over 1,300 measurements of T_b were made during 93 resting episodes. These data are still being analyzed; but it is apparent that marten exhibited considerable daily lability of T_b. Depression of observed T_bs below active levels did not exceed 5.1° C. Such a hypothermic state would produce a deep sleep, but not the torporous condition typical of true hibernators

	Arctic Tundra	Alpine Tundra	Boreal Forest	Northern Hardwood-Conifer Forest	Aspen Parkland	Montane Woodland	Pacific Rain Forest	Eastern Deciduous Forest	Grasslands	Oak Savannah	Northern Desert Scrub	Southern Desert Scrub	Mesquite Grassland	Pinyon Juniper	Chaparral-Oak Woodland	Southern Evergreen	Mexican Pine and Pine-Oak	Farmlands-Croplands
Canis latrans		•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•
C. rufus								•		•						•		
C. lupus	•	•	•	•	•	•	•	•	•	•	•	•	•	•			•	
Alopex lagopus	•																	
Vulpes vulpes	•	•	•	•	•	•	•	•	•	•	•			•	•	•		•
V. macrotis						•			•		•	•	•	•	•			
V. velox						•			•		•			•				
Urocyon cinereoargenteus				•		•	•	•	•	•	•	•	•	•	•	•	•	•
Ursus americanus			•	•	•	•	•	•		•	•	•	•	•	•	•	•	
U. arctos	•	•	•	•	•	•	•		•	•	•	•		•	•		•	
Bassariscus astutus						•	•			•	•	•	•	•	•	•	•	
Procyon lotor			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Martes americana			•	•		•	•											
M. pennanti			•	•		•	•											
Mustela erminea	•	•	•	•	•	•	•	•	•	•	•			•				•
M. nivalis	•	•	•	•	•			•	•	•								
M. frenata		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
M. nigripes									•		•		•	•				
Gulo gulo	•	•	•	•	•		•											
Taxidea taxus		•		•		•		•	•	•	•	•	•	•	•		•	•
Spilogale putorius								•	•	•						•		•
S. gracilis						•	•		•		•	•	•	•	•		•	•
Mephitis mephitis			•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Felis concolor			•	•	•	•	•	•		•	•	•	•	•	•	•	•	
F. lynx		•	•	•		•												
F. rufus			•	•		•	•	•	•	•	•	•	•	•	•	•	•	•

Figure 1.--Distribution of North American Carnivora with ranges mostly north of Mexico in major biomes mapped by Aldrich (1963). Biomes in which a species has occurred commonly in historic times are dotted. Mammal classification follows Jones et al. (1982).

Figure 2.--Numbers of resting sites (solid) and numbers of resting episodes (shaded) used by marten in the Snowy Range of southeastern Wyoming, winters of 1985-86 and 1986-87, by type.

(Swan 1974). We are currently looking at the relationships among weather factors, duration of resting episodes and depth of T_b depression during rest.

Fifty-seven resting sites used by marten during winter were characterized. Marten rested in sites that were generally associated with coarse woody debris or rockfields (fig. 2). The highest rates of reuse were observed in sites that were associated with logs or stumps or were beneath cabins (fig 2). We are currently looking at the distribution of winter resting sites in relation to mapped stand types and major topographic features.

Discussion

The close association of marten with old-growth stands, combined with the high monetary values of these stands and their long rotation times (Oosting and Reed 1952) cause us to anticipate that the marten is likely to be a sensitive species in management of subalpine forests of the central Rockies during the next two decades. As fragmentation of old-growth forests continues, managers will be increasingly pressed to document the responses of marten to this habitat alteration. An understanding of how management practices influence the habitat mosaic provided to marten, including their use of and dispersal through various cover types, and use of corridors between critical habitat components will be necessary. Ultimately, habitat requirements that provide for the genetic and demographic viability of populations through will have to be described.

Our research addresses key components of the functional importance of old-growth features to marten thermoregulatory behavior. How marten thermoregulate by modulating T_b, how they use protected microenvironments to minimize heat loss, and how their use of microhabitats varies with weather may go far to explain why marten are so closely associated with old-growth, during winter. A solid understanding of the criti-

cal habitat components of this species will provide a more meaningful definition of what marten ecological features marten may indicate, and how marten may be more effectively managed in forest ecosystems in the future.

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Control of Dwarf Mistletoes with a Plant Growth Regulator

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Abstract--This paper summarizes test results of ethephon, an ethylene-releasing plant growth regulator, as a control for two dwarf mistletoes: *Arceuthobium americanum* on *Pinus contorta* and *A. vaginatum* subsp. *cryptopodum* on *P. ponderosa* in Colorado. Ethephon at 2,500 ppm with a surfactant was tested using three application methods: a bottle sprayer, a backpack mistblower, and a hydraulic sprayer. Dwarf mistletoe shoot abscission rates of 74% to 100% were consistently achieved using these ground application methods. Mistletoe seed dispersal the year after ethephon application was much less in the treated plots than in the nontreated control plots. An evaluation of aerial application methods is in progress.

Dwarf mistletoes, *Arceuthobium* spp., are parasitic seed plants. They are regarded as one of the most damaging disease agents of conifers in the United States. An estimated 418 million cubic feet of wood fiber is lost annually to these pathogens either through growth reduction or tree mortality (Drummond 1982). These obligate parasites also lower wood quality and reduce cone and seed production of infected trees.

It has long been felt that an effective, safe, and economical chemical control of dwarf mistletoes would significantly reduce the impact of a major forest disease, especially in high-value stands, recreational areas, seed orchards, and ornamental plantings around homes, cabins, and business establishments.

Much successful research has been done on silvicultural control of dwarf mistletoes. But until recently, no effective chemical control had been found. Livingston and Brenner (1983) tested ethephon on *A. pusillum* on black spruce, *Picea mariana*, and consistently achieved 74 to 100 percent abscission of dwarf mistletoe shoots. They predict that abscission of aerial dwarf mistletoe shoots can prevent the spread of this disease in treated black spruce for at least 2 years.

Ethephon is quite safe and is routinely used on food crops to promote the abscission of leaves and fruits (DeWilde 1971). As ethephon is absorbed into plant tissues, ethylene is released, causing susceptible plant parts to abscise. There are no toxic by-products when the compound breaks down. Ethylene also exists naturally in conifers and is presumably responsible for natural abscission of aging dwarf mistletoe shoots. Based on these facts and the encouraging results achieved in the eastern dwarf mistletoe study (Livingston et al. 1985), we decided to test ethephon on two other extremely damaging dwarf mistletoe species in the western United States: *A. americanum* on lodgepole pine and *A. vaginatum* subsp. *cryptopodum* on ponderosa pine.

Methods

Studies of ethephon control of *A. americanum* on lodgepole pine were conducted in Colorado on the Fraser Experimental Forest from 1983 to 1986 and at Cutthroat Bay in the Arapaho National Recreation Area in 1985. We also set up a preliminary study on *A. vaginatum*-infected ponderosa pine near Meeker Park, Colorado, in the Roosevelt National Forest in 1985. Ethylene-releasing agents containing ethephon, Florel® and Ethrel,® at 2,500 ppm in water with a surfactant were tested on *A. americanum*, using three ground application methods: a bottle sprayer, a backpack mistblower, and a hydraulic sprayer. A bottle sprayer was used to apply ethephon, at the same concentration, to *A. vaginatum*. Two methods of evaluating the effectiveness of the treatments were used: the 6-Class Dwarf Mistletoe Rating (DMR) (Hawksworth 1977) and the Total Dwarf Mistletoe Area Rating (square inches) (Nicholls et al. 1987). Also, aerial applications of 1,200 and 2,400 ppm ethephon with surfactants were tested in 1986. Details of all 1983 to 1986 application and

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evaluation methods are in the paper by Nicholls et al. (1987) or in progress reports on file at the North Central Forest Experiment Station. This paper summarizes those results.

Results and Discussion

Dwarf mistletoe shoot area abscission rates of 74 to 100 percent (table 1) and DMR abscission rates of 30 to 100 percent (table 2) were achieved using ground application methods. Most shoot abscission occurred within 2 to 5 weeks after ethephon was applied (fig. 1). Mistletoe seed dispersal the year after ethephon application was significantly less in treated plots than in nontreated control plots. The bottle sprayer worked well for treating individual infections; the backpack mistblower worked well for trees 10 to 15 ft. tall; and the hydraulic sprayer was useful for trees up to 55 ft. tall. Some foliage turned brown on lodgepole pine and ground juniper (*Juniperus communis* subsp. *alpina*) when the hydraulic sprayer was used. This was probably due to the increased volume of ethephon solution that was applied with the hydraulic sprayer. Approximately 1 gallon of solution per tree was applied with the hydraulic sprayer; 0.4 gallon per tree was applied with the mistblower. However, the next year's buds and foliage developed normally.

Ethephon does not destroy the parasite's endophytic system in the host tissue. Therefore, new shoots began developing on some infections 1 to 2 years after treatment (fig. 2), and some shoots produced a few seeds 3 years after treatment. However, it will take time for the parasite to replace the large masses of mature shoots and seed that abscised after treatment. Therefore, we expect seed production and dissemination to be greatly reduced during this period. Because *A. americanum* and *A. vaginatum* have approximately 6 to 7-year life cycles, we feel that ethephon control will prevent or reduce significant spread and infection of dwarf mistletoe for up to 4 years and, perhaps, longer.

Table 1.--Percent reduction of Arceuthobium americanum and A. vaginatum female and male shoot area caused by 2,500 ppm ethephon compared to control treatments (N = 652 individual infections), Colorado, 1983-1985.

Study area	Treatment	% Total shoot area reduction Female	Male
A. americanum			
Sage (1983)	Ethephon/surfactant	89	95
	Ethephon/surfactant/DMSO1	74	100
	Control water/surfactant	4	9
Fool (1983)	Ethephon/surfactant	93	100
	Control water/surfactant	10	0
Gage (1984)	Ethephon/surfactant	97	99
	Control water	62	55
Headquarters (1985)	Ethephon/surfactant	97	100
	Control water	0	5
Cutthroat Bay (1985)	Ethephon/surfactant	78	87
	Control	0	0
A. vaginatum		(female and male combined)	
Meeker Park (1985)	Ethephon/surfactant	78	
	Control	0	

1DMSO = Dimethyl Sulfoxide

Table 2.--Percent 6-class Dwarf Mistletoe Rating (DMR) reduction of Arceuthobium americanum on lodgepole pine caused by 2,500 ppm ethephon compared to control treatments (N = 102 individual trees), Arapaho National Forest, Colorado, 1985.

Study area	Treatment	% DMR reduction
Cutthroat Bay		
Overstory trees	Ethephon/surfactant	30
	Control	0
Understory trees	Ethephon/surfactant	81
	Control	0
Fraser Experimental Forest		
Overstory trees (Area 1)	Ethephon/surfactant	70
	Control	0
Overstory trees (Area 2)	Ethephon/surfactant	90
	Control water	0
Understory trees (Area 2)	Ethephon/surfactant	100
	Control water	0

Aerial application of ethephon is currently being evaluated. This method may be useful in large stands of high recreational-value with understory regeneration. By controlling dwarf mistletoe in overstory trees, it may be possible to protect the understory trees from infection until they reach a size where dwarf mistletoe impact is less serious.

Mistletoe shoot abscission was not observed after the 1986 aerial application of ethephon. Although it is possible that the evaluation methods were not sensitive enough to measure effects, a more likely explanation is that not enough ethephon was applied to the plots to be absorbed by the mistletoe plants. The 10 gallons per acre applied in this study is much lower than the volumes applied during the successful ground applications: approximately 200 to 240 gallons per acre in the mistblower and hydraulic sprayer studies.

Conclusion

An effective, safe, and economical control of dwarf mistletoes would significantly reduce the impact of a major forest disease, especially in high-value stands. It would also provide forest managers with another control option to use in conjunction with silvicultural control methods.

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Figure 1. Ethephon control of *Arceuthobium americanum* on lodgepole pine: Presence of aerial shoots before and 5 weeks after ethephon was applied with a hand-held bottle sprayer, Fraser Experimental Forest, Colorado.

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Figure 2. Ethephon control of *Arceuthobium americanum* on lodgepole pine: Presence of aerial shoots before and 3 years after ethephon was applied with a hand-held bottle sprayer, Fraser Experimental Forest, Colorado.

Effect of Management on Nutrient Dynamics in Southwestern Pinyon Juniper Woodlands

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Abstract--Pinyon and juniper trees cycle nutrients producing a mosaic nutrient distribution that is vulnerable to range improvement, grazing, and fuelwood harvesting activities. Prescribed fire releases small amounts of available nutrients, but also volatilizes large quantities. These impacts on nutrient cycling may affect long term productivity of pinyon juniper woodlands.

Pinyon juniper woodlands occupy 62 to 79 million acres in the western United States (Arnold et al. 1964) and about 15 million acres in Arizona and New Mexico (Springfield 1976). These woodlands, which occur in the transition zone between semiarid vegetation (chaparral, desert shrub or grasslands) and coniferous forests, are characterized by a mosaic of pinyon and juniper trees; interspace areas are occupied by sparse to dense herbaceous and shrubby vegetation.

Pinyon juniper stands are found on a wide variety of parent materials; soils vary in texture from stony, cobbley, and gravelly sandy loams to clay loams and clay, and vary in depth from shallow to deep (Aldon and Brown 1971, Pieper 1977, Springfield 1976). In pinyon juniper woodlands a soil nutrient mosaic pattern develops where carbon, nitrogen (N), and available phosphorus (P) are concentrated in the upper soil layers under the tree canopy. This pattern reflects the accumulation of litter by different plant species (Barth 1980, Charley and West 1975, Everett et al. 1986, Lyons and Gifford 1980, Klopatek 1987). Tree growth rates vary widely between sites in close proximity to one another. Since pinyon juniper woodlands occur in different climatic regimes, and on a wide variety of soil types, these variable growth rates suggest nutrient limitations may exist similar to those found in other forest ecosystems. Although N is usually considered the most limiting nutrient in forest ecosystems (Maars et al. 1983), it appears P and potassium (K) may also be limiting (Barrow 1980, Bunderson et al. 1985).

Past management has emphasized tree removal for range forage improvement, but recently interest has increased in harvesting pinyon and juniper trees for fuelwood. Prescribed fire has been used extensively during both range improvement and slash disposal after fuelwood harvesting. Intensive tree removal and prescribed fire, coupled with continued use for grazing, is expected to alter naturally occurring nutrient cycling processes in these woodlands and thereby affect long term interrelationships among site productivity, succession, and tree growth (Miller at al. 1981, Young and Evans 1981). This paper presents information on distribution of nutrients and their cycling in pinyon juniper woodlands, and assesses the effect of different management strategies.

Nutrient Cycling and Distribution

Pinyon and juniper trees cycle nutrients both horizontally (Tiedemann 1987) and vertically (DeBano et al. 1987). Tree roots penetrate into interspace soils between tree canopies where they absorb nutrients and incorporate them into tree biomass. A large portion of the nutrients captured from interspaces are deposited on the soil surface under trees during leaf fall, where they are released in an available form by decomposition, thereby enriching the upper soil layers. Trees also translocate nutrients vertically to the soil surface from deeper in the soil profile by a similar process. The quantity of nutrients cycled by trees varies considerably from one locality to another, depending upon land use, climate, soil, and tree density and size.

Published information on nutrient patterns in pinyon juniper woodlands clearly portrays strong vertical and horizontal distribution patterns developing from the above described nutrient cycling regime. The most important vertical compartments are: above ground biomass, litter, and soil nutrients. Nutrients are also distributed and exchanged horizontally between trees and interspaces, resulting in larger amounts of

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nutrients being present in the living biomass and litter trees compared to interspaces. The quantities of nutrients stored in soils under tree canopies has been reported by some authors to be greater than in interspaces (Everett et al. 1987, Tiedemann 1987), while in other cases no significant differences could be detected (DeBano et al. 1987). Information presented in the literature on N, P, and K were used to develop a model portraying vertical nutrient distribution patterns under trees and in associated interspaces for a typical pinyon juniper ecosystem (table 1). Data on N presented in table 1 for a pinyon juniper ecosystem was taken from Tiedemann (1987). Distributions of P and K were taken from DeBano et al. (1987), where soils data for the 0 3.8 cm depth was extrapolated linearly to 60 cm. Important features of the vertical distribution pattern are: (1) a small percentage of the total nutrient pool resides in plant biomass and litter, and (2) the three nutrients differed in the proportion of a nutrient stored in living biomass and litter. For example, under tree canopies higher proportions of N are present in litter and above ground biomass compared to P and K. About 98 percent of total P in the tree ecosystem is contained in soil, compared to 93 percent for K, and 82 percent for N. Horizontally, N, P, and K are concentrated in a mosaic pattern corresponding to litter and canopy distribution. Although total N, P, and K in the soil may or may not differ significantly beneath tree canopies and interspaces, more total N, P, and K accumulates in live tree boles, stems, and leaves and in litter under tree canopies than in interspace vegetation (DeBano et al. 1987).

Nutrient Availability

Available and total nutrients are delicately balanced because only a small percent of the total nutrient pool is in a readily available form. Vertical and horizontal distribution patterns of available and total nutrients are similar. Horizontal patterns of nitrate N and ammonia N are influenced by tree canopy distribution, with higher concentrations of ammonia N being found in the surface soil under tree canopies compared to interspaces (DeBano et al. 1987). In contrast, nitrate N may or may not differ between trees and interspace areas (DeBano et al. 1987, Klopatek 1987, Thran and Everett 1987).

Management Implications

Information on nutrient dynamics can be used for assessing the effect of different management strategies on the nutrient status and productivity of pinyon juniper woodlands. Important strategies include: grazing, fuelwood harvesting, and using prescribed fire either for type conversion or slash disposal following fuelwood harvesting. Tiedemann (1987) estimated N losses over a 100 year period would be 340 kg/ha by grazing and 856 kg/ha if chaining and burning were used for cover conversion. In contrast, fuelwood harvesting over the same 100 year rotation would remove only about 133 kg/ha of

Table 1.--Amounts of nitrogen, phosphorus, and potassium (kg/ha) in above-ground biomass and the 60-cm soil depth under trees and associated interspaces in pinyon-juniper woodlands, and percent in each ecosystem compartment.

Ecosystem compartment	N[1]		P[2]		K[2]	
Trees						
Foliage	108	(1)	20	(<1)	147	(4)
Twigs	184	(2)	11	(<1)	55	(1)
Wood	133	(2)	5	(<1)	21	(<1)
Litter	1,000	(12)	44	(1)	65	(2)
Soil (0-60 cm)	6,615	(82)	3,963	(98)	3,584	(93)
Total	8,040		4,043		3,872	
Interspaces						
Foliage	4	(<1)	0.2	(<1)	0.2	(<1)
Soil	4,527	(>99)	3,963	(>99)	3,584	(>99)

[1]Data from Tiedemann 1987.

[2]Data from DeBano et al. 1987.

[3]Percent of total nutrient pool made up by a particular ecosystem compartment.

N in the woody material. However, if prescribed fire was used for slash disposal following harvesting, an additional 277 kg/ha of N would be volatilized from twigs and leaves (if 95 percent of the N is volatilized) in addition to variable amounts of the 1000 kg/ha of N contained in the litter. If large amounts of litter were consumed by fire during slash disposal operations, then an additional 400 500 kg/ha of N could be lost. It is not known how grazing would affect P and K pools.

Fuelwood harvesting would remove only a small percentage of the P (5 kg/ha) and K (21 kg/ha) nutrient pools during a 100 year rotation. Substantial P would also be lost if the leaves and twigs were burned following fuelwood harvesting. Nonparticulate losses up to 50% of the total P (16 kg/ha) could occur if these fine materials were totally consumed during burning (Raison et al. 1985). A variable amount of the P contained in the litter could also be lost, depending on the intensity of the fire. Similar percentages of K may also be lost because it volatilizes at the same temperature as P (Raison et al. 1985).

The effect of different management activities on available nutrients is not as well understood as on total nutrient pools, although there is some information available on the effect of fire on nutrient availability. Studies in pinyon juniper and other ecosystems show fire acts as a rapid mineralizing agent, and releases ammonia N which is later converted to nitrate N when conditions are favorable for nitrification (Klopatek 1987). The release of highly available forms of N by fire portrays the impression that burning increases soil fertility on a site. However, total N is reduced, and increases in ammonia and nitrate N are short lived because these nutrients are rapidly immobilized biologically. Inorganic P also is released by burning, but it too is quickly immobilized chemically (DeBano and Klopatek, In press) and may no longer be readily available for plants. Harvesting also increases the concentration of nitrate N in soil surface layers (DeBano et al. 1987). Nitrate N

presumably increases because harvesting reduces inhibition of nitrification, eliminates trees which assimilate any nitrate N being formed, or changes the microclimate. Both soil moisture and temperature can be increased by harvesting (Everett and Sharrow 1985) which in turn may affect microbial relationships.

Summary and Conclusions

Pinyon and juniper trees enrich the surface soil beneath their canopies by cycling plant nutrients, both vertically from the subsoil and horizontally from adjacent interspaces. This produces a spatial distribution of nutrients roughly corresponding to existing tree canopy cover. Both N and P undergo extensive horizontal and vertical translocation. Important features of this vertical distribution pattern are: (1) a small percentage of the total nutrient pool resides in plant biomass and litter, and (2) N, P, and K differ in the proportion of a nutrient stored in living biomass and litter. The location of active nutrient pools beneath tree canopies makes them vulnerable to different management practices such as range improvement and fuelwood harvesting. Prescribed fire is used in both range improvement and slash disposal after fuelwood harvesting. Range improvement practices designed to permanently convert pinyon juniper stands to grasslands may have a major impact on the storage and cycling of both above and below ground nutrients, particularly if chaining and burning are used as part of the treatment. Fuelwood harvesting not only removes nutrients directly from the site, but also affects mineralization and the release of available nutrients remaining on the site. Prescribed fire acts as a rapid mineralizing agent, making part of the nutrient pool more readily available but at the same time volatilizing substantial amounts of nutrients from the litter and above ground biomass. These losses and changes in nutrient pools may affect the productivity of pinyon juniper woodlands.

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2H5

Glacier Lakes Ecosystem Experiments Site: An "Experimental" Wilderness

Douglas G. Fox, Anna W. Schoettle, and Frank A. Vertucci[1]

Abstract--This site, selected to be representative of high-mountain wilderness ecosystems, is being used to study the effects of air pollution and atmospheric deposition in alpine and subalpine, terrestrial and aquatic biotic communities. The research program includes (a) short-term experiments designed to quantify the response of system components hypothesized to be most sensitive to changes in ozone, S, and N air pollution and deposition; (b) development of operationally oriented models capable of predicting system, species, and biogeochemical responses; and (c) long-term biogeochemically-oriented monitoring to help establish the validity of (a) and (b) as management decision tools.

Wilderness is the most rapidly increasing land use within the National Forest System. Wilderness presents a unique set of challenges to managers. To date, management has largely been confined to controlling or minimizing visual effects. However, other stresses are operating in complex ways that cannot be seen. Of particular concern are effects caused by air pollution, and combinations of air pollution and climate change hypothesized to result from increasing human populations. A logical first step in scientifically based wilderness management involves monitoring these ecosystems over time. We have recently developed guidelines for this purpose (Fox, et. al. 1987).

It is well known that ecosystems change in response to natural internal dynamic processes as well as to both natural and anthropogenic external stresses. Our present knowledge of wilderness ecosystems does not allow us to distinguish the subtle differences between these change-causing factors. However, prudent management of wilderness requires that ecosystem effects resulting from changes in the chemical and physical climate be understood. From such understanding will develop management alternatives to help maintain these wildernesses as areas substantially "uninfluenced by the hand of man."

Just as we have learned how to manage commercial forest ecosystems through carefully controlled research studies, so also will we learn to manage wilderness by studying it. The research, however, is different from what has been done in the past. Questions involve sorting out the role of unseen stressing factors, components of the general environment, on ecosystem health. Issues relate to maintaining rare and endangered species where pertinent. Debate about the appropriate manner to gauge ecosystems, whether on a species or a functional level, must be resolved. Ensuring the vast biotic diversity among wildernesses is a new and unprecedented management objective.

These complex questions require research that considers the system from different perspectives. Research will require studying the response of tightly defined ecosystems to atmospheric inputs. Figure 1 illustrates the components of an ecosystem. The boxes represent transfers between components. The challenge in ecosystem research is constructing boundaries around these components that allow a mass balance of fluxing chemicals to be constructed with some accuracy. These "ecosystems" might be an entire watershed, a few tens of meters of a stream, or a very carefully isolated 1 m^2 patch of alpine soil. Common to all these differently defined ecosystems will be the ability to construct accurate nutrient budgets and to study, in a self-contained manner, processes of and interactions between the organisms and abiotic factors that consume, alter, and generate these nutrients. Species and community level dose/response experiments are being conducted to evaluate specific response hypotheses. Process-based models will be constructed to try to incorporate individual responses into system-level behaviors. Long-term monitoring data will be required to ensure the validity of hypotheses and models in the natural landscape.

Conducting such an extensive research program is incompatible with legally mandated wilderness. Rather, a location is required that (a) is not formally designated wilderness but has current and past uses like wilderness, (b) is remote but accessible year round, and (c) contains ecosystems that can be hypothesized to be sensitive to air pollution, acid deposition,

[1]Douglas G. Fox, Project Leader; Anna W. Schoettle, Plant Physiologist; Frank Vertucci, Aquatic Ecologist, USDA Forest Service.

and climate change. To find the best possible location for this research program, we spent 2 years evaluating potential locations. This involved a large number of scientists and a field season of data collection before the final site was selected.

Selection was based on a set of criteria that included logistical factors (ownership, permission to conduct research, accessibility, historic data) and ecological factors (excellent air quality, alpine/subalpine type, nonweatherable bedrock, lakes, water with ANC < 50 ueq/l, soils with base saturation less than 25%). Ecological criteria were based on the hypothesis that currently unimpacted systems exhibiting low buffering capacity are likely to be maximally sensitive to air pollution inputs. The buffering capacity was gauged by acid neutralizing capacity (ANC) of the surface waters, relative mineral weathering potential of bedrock, and exchange capacity of the soils. An alpine location was desired that collects large amounts of snow. The snowpack effectively accumulates and stores pollution on the site until spring melt. Spring brings a pulse of chemicals delivered rapidly to the ecosystem. This can result in a temporary change in lake chemistry which, depending on lake pH, may cause changes in the biotic complex. Such a location is clearly the most sensitive from an aquatic perspective. In clean air, ozone concentrations tend to increase with elevation. Climate influences are dominant factors in the alpine, tree line providing a dramatic example. It is therefore reasonable to hypothesize that alpine locations will be most sensitive from a terrestrial perspective as well.

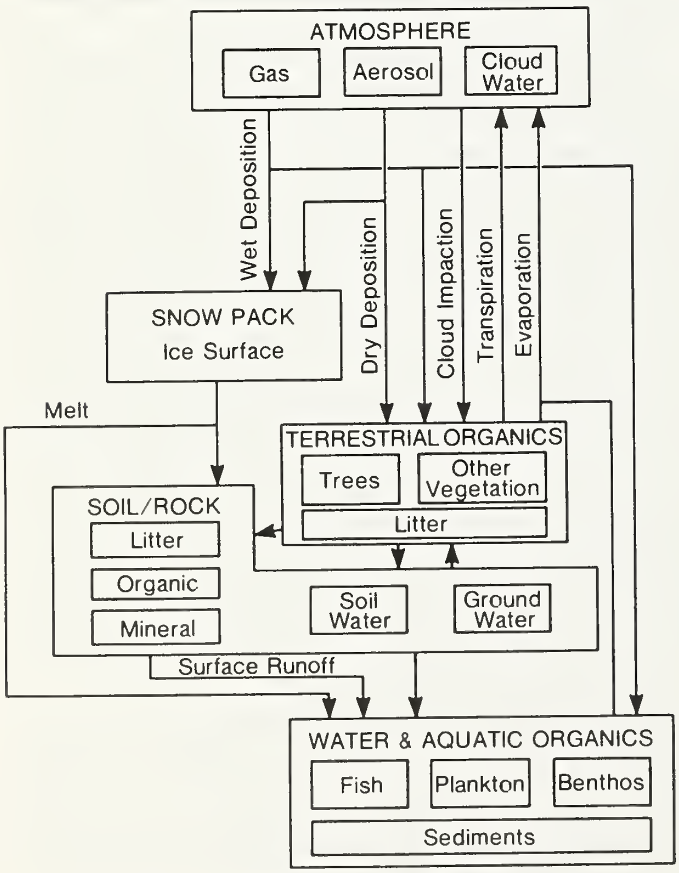


Figure 1.--Box and line diagram of GLEES.

All these criteria are met at the Glacier Lakes Ecosystem Experiments Site (GLEES).The site and the research program currently underway there are described in the remaining sections of this paper.

GLACIER LAKES ECOSYSTEM EXPERIMENTS SITE

Location and Topography

GLEES is located on the Medicine Bow National Forest approximately 65 km W of Laramie, Wyoming. The site is a high (3,400 m) glacial cirque basin, containing three small lake watersheds (104, 52, and 43 ha) fed by first-order perennial streams generated from permanent snow fields (fig. 2). Vegetative cover is primarily subalpine, with a sparse Engelmann spruce-subalpine fir forest (including krummholz stands), forb-dominated snowpatch communities, and sedge meadows. Soils are minimally developed. Geologically, the basin is uniform quartzite (75-80%) crossed by intrusions of amphibolite, a mineralogically complex and active mafic rock. Water chemistry is dominated by snow chemistry except for streams that run through sufficient mafic materials to reflect weathering processes. Lake water is extremely low in ionic strength; alkalinities are on the order of 40 ueq/l.

Meteorology and Air Quality

Data have been collected in the vicinity of the Glacier Lakes since the late 1960's, primarily for measuring the contribution of the Snowy Range to Wyoming water resources (Wesche 1982). Mean temperatures measured near the watershed range from lows of -10° F to highs of 30° F in winter and lows of 20° F to highs of 70° F in summer. Wind speed, on the exposed locations of the watershed, can average above 15 mph for months at a time. Precipitation is highly variable across the watershed but averages 35 inches at Lost Lake, 42 inches between East and West Glacier Lakes, and 49 inches near the East Glacier Lake outlet.

Although no air quality measurements have yet been recorded, the area is assumed to be clean based on the chemistry of precipitation. A wet/dry precipitation collector operated by the Wyoming Water Research Center for the National Acid Deposition Program on the southwest side of West Glacier Lake since April, 1986, indicates sulfate and nitrate concentrations generally below western averages.

Air quality measurements will be initiated on the watershed in 1987.

Geology and Soils

The geology of GLEES has recently been described by Rochette (1987) and the soils by Hopper and Walthall (1987). Local alpine glaciation caused three cirques or nivation basins

Figure 2.--The GLEES contour and geologic map. Dashed lines illustrate mafic dykes into the surrounding quartzite. The geological mapping is only in the boxed areas.

to form on the south side of the primary ridge line. Bedrock is quite uniform, consisting of Medicine Peak quartzite intruded with 15-20% mafic dykes of amphibolite. The significance of the mafic rock is that it is considerably richer in minerals. The chemistry of surface waters in the streams feeding West Glacier Lakes appears to be dominated by weathering of the mafic rocks. Nevertheless, this weathering rate is not likely to increase with acid deposition, and because of minimal soil-water contact, the watersheds are considered quite sensitive to increases in acid deposition (e.g., the watershed buffering capacity is small) (Rochette 1987).

Vegetation

The watersheds are predominantly subalpine with considerable abundance of alpine taxa (Simmons 1987). The forested areas (35% of the area) are Engelmann spruce- subalpine fir, which also form krummholz stands at more exposed locations (fig. 3). An occasional limber pine can be identified. A total of 135 plant taxa have been identified on the watersheds. Many are alpine species, particularly in the meadow and cushion-plant assemblies. Herbaceous vegetation types (meadows, cushion-plant-dominated ridge tops, and partially vegetated scree) make up 30%, while willow-shrub types (willow and wet meadow willow) comprise the remaining 5%, which is significantly vegetated.

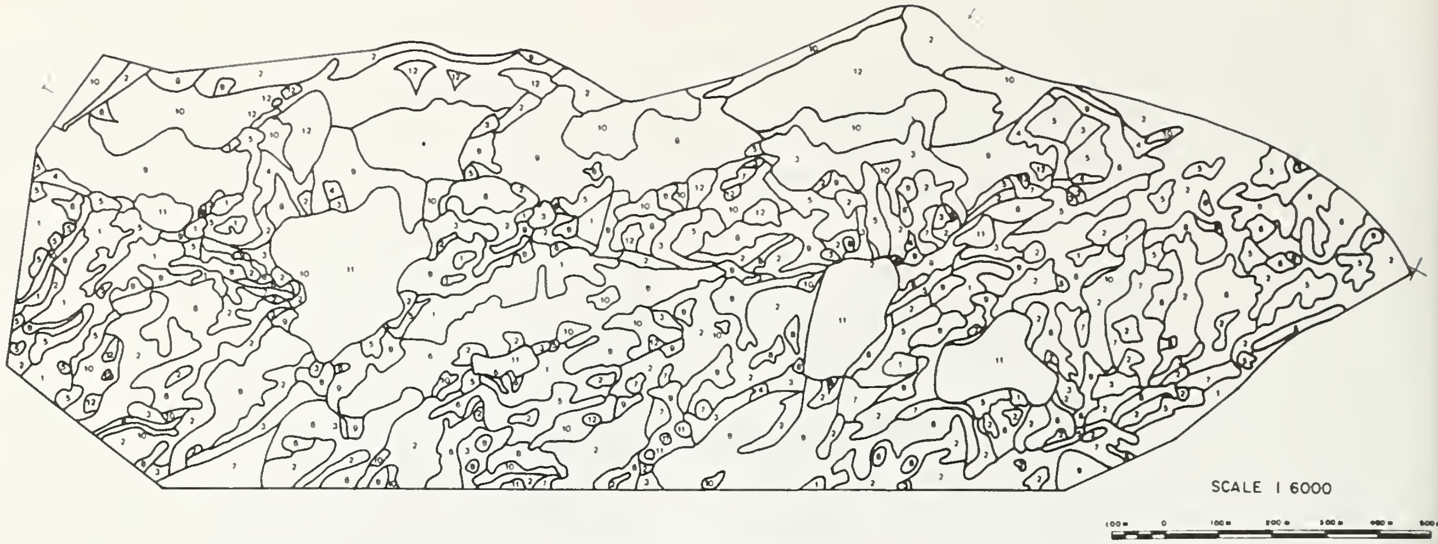
Lakes and Streams

Lost Lake is the largest (6 ha) and highest (3332 m) of the three lakes. East Glacier Lake is 2.8 ha with a watershed of approximately 43 ha. West Glacier Lake is 2.6 ha with a watershed of approximately 52 ha. Four streams, as shown in figure 2, feed West Glacier Lake. Inflow to East Glacier Lake is largely accomplished by nonchannelized flow and therefore, appears to be relatively more subject to interactions with watershed soils and vegetation.

Lakes and the West Glacier outlet stream support brook trout populations. In addition, East Glacier supports a cutthroat trout population. Macroinvertibrate sampling suggests a relatively depopulate community of cold water species in the stream. Lake and stream acid neutralizing capacities are low ranging between 30 and 50 ueq/l.

THE RESEARCH PROGRAM

The site will be used for long-term ecosystem study. The study will be watershed oriented, namely individual watersheds and subcatchments within these watersheds will be identified, gauged, and studied. Figure 1 can be used to represent a simple conceptual model of the GLEES. Our research plans include measurement of the reservoirs and as many of the transfers as are practical. Within this framework,



KEY TO VEGETATION/LANDSCAPE TYPES

1 Cushion Plants/Stone Pavement
2 Meadow
3 Willow Shrub/Wet Meadow
4 Scree/Meadow
5 Krummholz Conifer>60 % cover
6 Krummholz Conifer 20-60 % cover
7 Coniferous Forest>60 % cover
8 Coniferous Forest 20-60 % cover
9 Scree
10 Rock Outcrop
11 Water
12 Snow

Figure 3.--Vegetation and landscape types on the GLEES.

detailed budgets associated with the reservoirs themselves will be constructed. Where possible, paired systems will be identified or constructed so that manipulation experiments can be conducted with controls.

Atmospheric Compartment

The careful measurement of atmospheric input to the GLEES will be a hallmark of this research. In addition to measurements, the Topographic Air Pollution Analysis System (TAPAS), a comprehensive set of meteorologically based state-of-science computer simulation models will be used to help characterize the atmospheric compartment. Specific studies include:

Meteorology.--The objective of meteorological studies is to characterize the overall meteorology and climate of the GLEES. The relatively uniform terrain of the GLEES allows a minimum of measurements to accomplish this (fig. 4). Instrumentation has been installed at two locations on the GLEES. At each a tower has been erected well above the forest vegetation. Both are instrumented with wind speed, direction, temperature, and humidity. Planned expansion includes multiple levels of turbulence and radiation instrumentation.

Air Quality.--The objective of air quality measurement is to help characterize chemical inputs to the GLEES. It is a measure of the amount of chemicals in the atmospheric compartment and helps in the measurement of dry deposition, one of the major unknown transfers from the atmospheric compartment.

Wet Deposition.--The objective of wet deposition measurement is to further characterize chemical inputs to the GLEES. It also is a major transfer from the atmospheric compartment. A wet deposition collector has been operating at the site since Spring, 1986. Additional bulk precipitation samplers will be installed at various locations on the GLEES in order to establish input chemical variances.

Dry Deposition.--The objective of dry deposition research is to try to directly measure this most illusive component of atmospheric transfer. To date no dry deposition measurement has been made in a complex-terrain forested setting.

Snow Pack Compartment

Snow pack is considered a separate component of the ecosystem because of its importance to the collection and delivery of air pollution and deposition to alpine systems. One cubic meter of snow contains approximately 104 square meters of surface area, about 2 football fields. This vast surface area is available to collect and hold pollution. Considerable research on snow chemistry and physics processes is underway within the Atmospheric Deposition Effects research unit. An ambitious field research program centers around an attempt to characterize the rapidly changing chemistry of melting snow.

Terrestrial Organic Compartment

Our interests in the terrestrial compartment are both with the transfer of atmospheric chemicals and nutrients into this compartment and with dose/response studies of selected

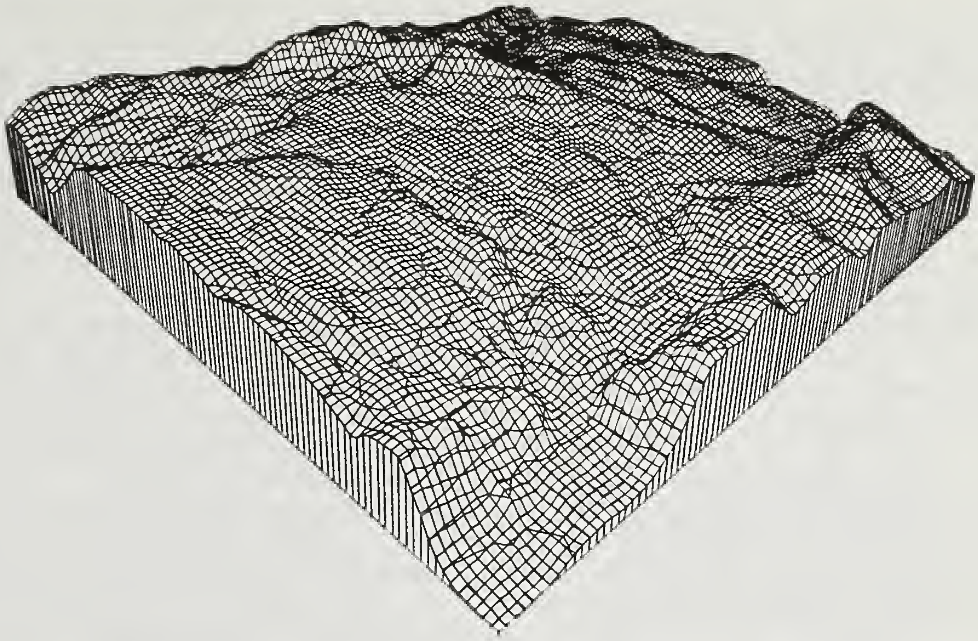


Figure 4.--A three-dimensional perspective of the GLEES vicinity. The maps in later figures cover the boxed area. Centennial is located in the lower corner of the map. The map was produced by the Topographic Air Pollution Analysis System (TAPAS) (Fox, et.al. 1986).

species within this compartment. The objective of this research is to establish the relative sensitivity of the alpine floristic component of the GLEES to air pollution and deposition. The first step in this research is to attempt to use a combination of physiological and morphological information to screen plants for their theoretical sensitivity. This is a field activity that will be conducted at the GLEES. The second step requires manipulation of the "theoretically" sensitive plants by subjecting them to elevated pollution and deposition.

Soil, Rock and Ground Water Compartment

A soil map of the GLEES has already been prepared. The ability of the soil to consume H^+ will be studied using the soil map along with laboratory studies of the soil chemistry such as SO_4 and NO_3 sorption, cation leaching, etc.

Water and Aquatic Organics Compartment

Stream Study

The chemistry and biology of a pair of streams, Cascade and Meadow, will be characterized. One stream will be manipulated by the input of sulfuric and nitric acid. Effects on the stream biota will be measured. This study will utilize the recently constructed gauging stations for each stream, input reservoirs at the stream head, drift nets and emergence traps (houses over stream).

Lake Studies

We also will attempt to characterize the role played by the lake in nutrient dynamics of the system. In addition to the morphometric survey already completed, sediment mapping and coring will be conducted including introduction of a paleolimnological tracer for the future. Seepage meters will be installed on transects in the lake bottom. The Parshall flumes in GLEES will be used to aid careful measurement of the hydrological balance of the watershed.

Fish surveys will be conducted as needed to determine the biomass and condition of this resource. Plankton productivity will be studied with small containers suspended in the lake closed to the system but containing carbon 14. Benthos will be surveyed by scuba divers.

SUMMARY

A broadly based ecosystem research program has been initiated on the Glacier Lakes, Medicine Bow NF, Wyoming. The ecosystem on the Glacier Lakes is alpine/subalpine and in a natural state. Minimal management activity is conducted on this area which is prototypical of much of the Wilderness system in the western US. The Glacier Lakes site can be considered an experimental wilderness. It is expected to exhibit extreme sensitivity to changes in atmospheric inputs of chemical nutrients and energy. The research program planned for the Glacier Lakes will provide new information for managers in the 21st Century. This information is likely to be

centered around increased world population and manifested in the form of increased recreational use of areas like the Glacier Lakes, and changed climate as a result of increased air pollution.

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Bird-habitat Relationships in Subalpine Riparian Shrublands of the Central Rocky Mountains

Deborah M. Finch[1]

Abstract--Breeding birds were counted in 1982, 1983, and 1984 using the spot-map method on seven 8.1-ha plots in the Medicine Bow National Forest, Wyoming. At elevations of 2,280 to 3,000 m, riparian habitats were structurally simple, dominated by one or more bush willow species. Subalpine riparian avifaunas were depauperate with only four abundant species-- song sparrow, white-crowned sparrow, Lincoln's sparrow, and Wilson's warbler. Habitat requirements overlapped among these species but differed significantly from randomly-sampled habitat in the same areas. Results indicated that species preferred densely-foliated ground and shrub layers, and higher effective vegetation height. Factors complicating efforts to characterize bird-habitat relationships are discussed.

Many factors complicate efforts to characterize relationships between wildlife abundance and habitat structure (Best and Stauffer 1986). These factors include population and species variability in time or space, measurement or sampling error, sampling scale, and inappropriate statistical methods. Models of wildlife-habitat relationships that are derived from limited or misrepresentative data sets produce indices that are not predictive or reliable.

Population size can vary from year to year, from season to season, and from site to site (Gaud et al. 1986). Factors that cause temporal and spatial variability in populations of terrestrial bird species include changes in weather and climate (Wiens 1981a, Szaro and Balda 1986, Hejl and Beedy 1986, Diehl 1986), qualitative and quantitative changes in food and habitat resources along environmental gradients (Karr 1980, Noon 1981a, Rice et al. 1983), and interspecific interactions (Terborgh and Weske 1975, Terborgh 1985). Error in estimating population size may result from observer differences, measurement error, inappropriate census methods, or insufficient sample size (Ralph and Scott 1980, Verner 1985, Stauffer and Best 1986). Scale of observation may affect evaluation of animal responses to habitat trends (Wiens 1981b, Wiens 1986, Maurer 1985, Morris 1987, but see Bock 1987). Sampling at a single site, multiple sites in a local area, or many geographical areas may produce different interpretations of species requirements, depending on the level of resolution.

A greater understanding of the factors that complicate interpretations of wildlife-habitat relationships is needed to reduce estimation error. Multiple year studies over a large number of sites, vegetation types, and localities are the best designs for explaining variation in bird abundance, but time and expenses may be prohibitive. In this paper, I examine associations between bird abundance, habitat structure measured at random sites, and habitat measured at bird locations in subalpine riparian shrublands. I considered the confounding effects of 1) year-to-year variation in numbers of four breeding bird species, 2) variation in bird abundance across sampling plots, 3) variation in species responses to habitat structure, and 4) sampling at plot and gradient levels of resolution.

Methods

Study Areas

Seven 8.1-ha study grids were established in the summer of 1981 in shrub willow habitats along drainages in the Medicine Bow National Forest of southeastern Wyoming (table 1). Each grid was posted at 33.5-m intervals with wooden stakes painted fluorescent orange and marked with grid coordinates. Grid dimensions were adapted to the variable widths of the streams

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Table 1.--Three-year (1982, 1983, 1984) means + standard deviations of numbers of spot-map pairs of four subalpine bird species counted on seven 8.1 ha riparian plots in the Medicine Bow National Forest, southeastern Wyoming. Plot drainages are arranged in ascending elevational order. F-ratios and probability levels of two-way ANOVA testing YEAR and PLOT effects on species counts are given.

Reference number	Drainage	Elevation (m)	Wilson's Warbler	Song Sparrow	Lincoln's Sparrow	White-crowned Sparrow
1	Wagonhound Creek	2,286	0	8.7 ± 1.8	0	0
2	S. Lodgepole Creek	2,470	0	10.3 ± 2.9	12.0 ± 4.6	0
3	N. Lodgepole Creek	2,530	0	9.0 ± 3.1	13.3 ± 2.2	0.3 ± 0.3
4	Douglas Creek	2,591	19.0 ± 2.7	3.0 ± 0.6	27.3 ± 3.5	8.0 ± 1.5
5	Lake Creek	2,789	5.5 ± 0.5	0	17.0 ± 0.0	4.0 ± 0.6
6	Lower Middle Fork Little Laramie River	2,930	6.0 ± 0.6	0	13.3 ± 1.7	4.0 ± 0.6
7	Upper Middle Fork Little Laramie River	2,987	6.0 ± 0.6	0	9.3 ± 0.3	10.0 ± 1.2
	F-Ratio (P)[a]					
	YEAR effect		3.18 (N.S.)	0.96 (N.S.)	0.15 (N.S.)	3.19 (N.S.)
	PLOT effect		4.99 (*)	6.50 (*)	22.40 (*)	31.65 (*)

[a]*$P < 0.01$, N.S. = not significant. Numerator and denominator degrees of freedom are 2 and 12 for YEAR effect and 6 and 12 for PLOT effect.

in the following combinations: 3 x 24 squares (plots 4, 5, 9 and 10); 2 x 36 (plot 6); 4 x 18 (plot 7); and 6 x 12 (plot 8).

Study grids were distributed over an elevational continuum ranging from 2,286 m to 2,987 m. Vegetation on plots 1 to 3 was dominated by one or several shrub willow species including *Salix bebbiana, S. exigua, S. geyeriana, S. planifolia, S. boothii,* and *S. lasiandra*. Additional shrubs that were locally common on these mixed willow plots were thinleaf alder *(Alnus tenuifolia)*, western snowberry *(Symphoricarpus occidentalis)*, common chokecherry *(Prunus virginiana)*, serviceberry *(Amelanchier alnifolia)*, and red-osier dogwood *(Cornus stolonifera)* (see Finch 1987 for complete shrub list). Small isolated patches of quaking aspen *(Populus tremuloides)* were also present. Surface understories were dominated by *Calamagrostis canadensis* and *Carex* spp. These drainages were typically bordered by sagebrush *(Artemisia tridentata)*, grassland, and lodgepole pine *(Pinus contorta)* forest.

On higher elevation (> 2,600 m) plots, *S. planifolia* was found in monocultures or mixed with *S. wolfii*. The subalpine parks formed by these willow thickets were associated with wet, boggy meadows of *Deschampsia cespitosa* and *Carex* spp., surrounded by mixed stands of Engelmann spruce *(Picea engelmannii)* and subalpine fir *(Abies lasiocarpa)*. A more detailed account of plant species distributions in the Medicine Bow Mountains can be found in Nelson (1974).

Sampling Bird Populations

Birds were counted on the seven study grids using the spot-map method (Robbins 1970) from mid-May through early July of 1982, 1983, and 1984. A minimum of eight visits was made to each study plot each year, and each visit lasted from 2 to 4 hours beginning at daylight. Edge clusters were counted as belonging to the plot if more than half of the observations were recorded within or on the plot boundaries. Netting and banding information were used to substantiate the presence of pairs in cases where mapping information was inconclusive (Verner 1985). See Finch (1986, 1987) for more details on procedures for counting birds, and overall count results.

Sampling Habitat Structure

Four bird species were selected for analyses of bird-habitat relationships based on their high relative abundances in subalpine riparian communities: Wilson's warbler *(Wilsonia pusilla)*, song sparrow *(Melospiza melodia)*, Lincoln's sparrow *(Melospiza lincolnii)*, and white-crowned sparrow *(Zonotrichia leucophrys)*. Habitat structure was sampled in July and August of 1982, 1983, and 1984 within the mapped territories of these four species, either near nest sites or at male singing locations. Bird-centered vegetation sampling was developed by James (1971) and recommended by Larson and Bock (1986) as a powerful tool for evaluating habitat relationships because it is precise and efficient, and because data can be pooled at various spatial scales (e.g., study plots, set of local plots, or geographical region). A total of 134 territories were sampled across the set of study plots. Sample data were pooled for each species to give estimates of associated habitat characteristics at each study plot as well as over all plots. These data were used to assess the effects of habitat variation among plots separately from species responses to habitat, but only values for habitat features averaged over all plots are reported here.

For comparison, 40 random locations in each study grid were sampled in a mode identical to the bird-centered samples. Random sampling sites were located by selecting grid coordinates from a table of random numbers. Random sample data were pooled to give estimates of habitat features for each plot and all plots combined.

At each sampling location, a set of 34 structural habitat variables was measured following a point-centered quarter sampling procedure recommended by Noon (1981b) for shrub habitats. Habitat features were sampled by dividing each location into four quadrants oriented in the cardinal compass directions. Twenty-one of the original variables were deleted from the final analyses because they were invariant, highly correlated with other variables, or irrelevant with regard to subalpine shrub habitats. Descriptions and sampling techniques for the remaining 13 variables are presented in table 2.

Data Analyses

Two-way ANOVA was performed to detect variation in number of pairs of each species among years and among study plots. Data for three years and seven plots were used to determine main effects of the two factors, YEAR and PLOT. Because no interaction was observed between YEAR and PLOT, the three-year bird count data were averaged for each species in other analyses.

Nested design analysis of variance was used to test for differences in habitat structure between random and bird-centered locations (BIRD effect) among seven plots (PLOT effect). Random and bird-centered sites were compared (nested) within each plot before PLOT effect was computed so that plot-to-plot variation in habitat structure would not interfere with assessment of bird-habitat associations. Each of the thirteen habitat variables was analyzed using a univariate approach. Only the BIRD effect is reported here in order to focus on the factor of main interest. Nested ANOVA's were also used to assess variation in habitat selection among the four bird species (SPECIES effect), and between all birds pooled versus random sites (ALLBIRD effect) across seven plots.

The relationship between trends in each habitat variable and numbers of pairs of each species across the seven plots was examined using Pearson product-moment correlation coefficients. Averaged three-year count data and averaged random habitat data for each study plot were used to produce positive or negative bird-habitat associations. Significant associations were determined using two-tailed t tests.

Analyses were performed using SPSS and SPSS Update 7-9 statistical packages (Nie et al. 1975, Hull and Nie 1981) and SPSS/PC+ programs (Norusis 1986). Analyses of raw and log-transformed variates (Kleinbaum and Kupper 1978) produced biologically and statistically similar results. Results of raw data analyses are reported here for ease of interpretation.

Results

Trends in Bird Numbers

Mean yearly numbers of avian pairs varied substantially among the four bird species over the seven study areas based on the results of a one-way ANOVA (F-test = 3.57, $P < 0.05$).

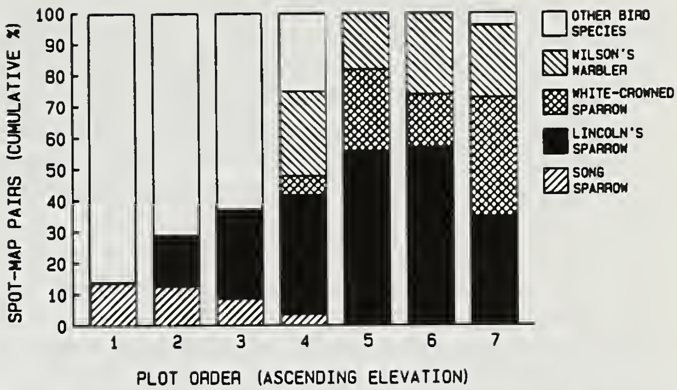

Figure 1.--Population trends of four subalpine bird species counted on seven study areas in 1982, 1983, and 1984. Counts are arranged by plot elevation.

In the three study years, song sparrow numbers declined with increasing plot elevation, disappearing altogether at higher elevations (fig. 1). The distribution of Lincoln's sparrow moderately overlapped with song sparrow, but showed an opposite trend of increasing numbers with ascending elevation (fig. 1). Wilson's warbler and white-crowned sparrow co-occurred on the four highest plots and were absent from lower study areas. Two-way ANOVA indicated that year-to-year variation in population numbers of each species was low compared to variation due to study area differences, and therefore averaged three-year counts were used in analyses of bird-habitat relationships (table 1).

On two of the lowest-elevation plots, Lincoln's sparrow and song sparrow shared the habitat with a complex bird species assemblage (Finch 1987), and as a consequence, both species comprised only 14-37% of the avifauna (fig. 2). In contrast, Lincoln's sparrow alone dominated the four higher subalpine plots, composing 35-57% of the avian community, followed by Wilson's warbler with 18-27% and white-crowned sparrow with 6-38% (fig. 2). These three subalpine species constituted 75-100% of the riparian avifauna censused at elevations of 2,600 m and above.

Avian Habitat Selection

Thirteen structural features were useful in describing within-plot habitat selection patterns of subalpine riparian bird species. In the ground layer of vegetation, vertical foliage density was significantly higher at sites occupied by Wilson's warbler and white-crowned sparrow than at randomly-measured sites, and in the low shrub layer, foliage was denser at sites selected by all four species than at random sites (table 2). Selection for dense foliation in the low shrub stratum is reflected in the significant variation in this habitat feature between random sites and all bird species pooled (ALLBIRD effect, table 2). Vertical foliage density in the tall shrub layer did not differ significantly between random and bird-centered sites. All four species also selected sites with greater-than-random effective vegetation height, which is an alternate

measure of vegetation volume. This habitat feature also varied among bird species (SPECIES effect) as well as between random sites and all birds pooled (table 2).

Song sparrow chose territorial sites within plots that had greater-than-random canopy cover, but the other three bird species showed no trend (table 2). Wilson's warbler and white-crowned sparrow strongly ($\underline{P}$ < 0.0001) selected sites that were thickly covered by shrubs < 1 m (mean cover > 44%) and other woody material (mean cover > 56%). In contrast, at random sites, small shrub coverage was only 28%, and coverage by woody matter was only 43%. To a lesser extent ($\underline{P}$ < 0.05), song sparrow also chose sites with greater shrub and woody cover, but Lincoln's sparrow was distributed in a close-to-random manner with respect to all ground cover features. Sites with grass/forb coverage as high as the random value of 52.5% were not used by Wilson's warblers and song sparrows, and Wilson's warbler also avoided sites with bare ground (table 2). Percent cover by small shrubs, grass/forbs, and bare ground varied substantially among the four species, but only small shrub cover varied between random sites and the entire group of species.

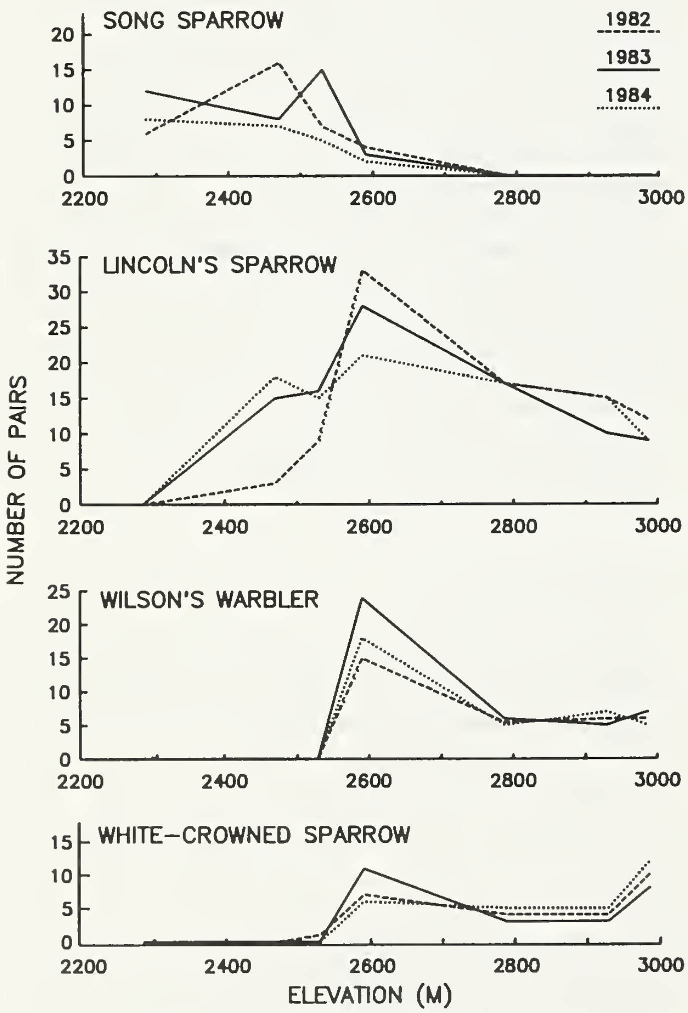

Figure 2.--Dominance patterns of four subalpine bird species based on number of territorial pairs counted on seven study plots listed by ascending elevation.

Wilson's warbler chose subalpine sites with lower shrub crown diameters and shrub height than random sites whereas song sparrow chose sites with larger-than-random shrubs. These two shrub size characteristics were also important in distinguishing among species locations within study areas (SPECIES effect, table 2). In contrast, shrub dispersion and percentage fruiting shrubs were shrub features that differed from random values at sites occupied by Lincoln's sparrow and white-crowned sparrow, as well as at locations selected by all birds (table 2).

Bird Densities and Habitat Trends

I used correlational analyses to identify relationships between mean 3-year counts of each species and mean habitat features over all study areas. This evaluation of abundance patterns substantiated patterns of habitat selection evident in the analyses of random versus bird-centered data, but detected other habitat selection trends as well.

Wilson's warbler plot densities were significantly and positively correlated to foliage density in the low shrub layer, effective vegetation height, and woody cover, and negatively associated with grass/forb cover (table 2). These relationships are similar to those found in the bird-centered habitat data. Numbers of song sparrows were also associated with several features relevant in the bird-centered habitat analysis; additionally, song sparrows increased in numbers on plots with greater foliage density in the tall shrub layer and higher mean shrub height. Higher numbers of Lincoln's sparrow were associated with plots that had high vegetation surface foliage density, and low percentages of bare ground cover and fruiting shrubs. Reduced canopy cover was the only habitat variable significantly associated with increased white-crowned sparrow densities.

Discussion

Temporal Effects

Abundances of four migratory nesting bird species remained relatively stable over the three-year study period, and therefore year-to-year variability did not confound attempts to interpret bird-habitat relationships. Although longer-term studies are needed to verify temporal stability in these subalpine riparian bird populations, other studies have indicated that only numbers of permanent residents varied significantly among years, probably because of severe over-wintering mortality (Beedy 1982, Raphael and White 1984, Hejl and Beedy 1986). Lack of year-to-year differences in migrant abundances in this study suggests that winter conditions were not harsh enough to depress numbers on the wintering grounds, and therefore no changes were observed on the breeding grounds.

Effects of Plot Variation

Population size of all four bird species varied substantially across sampling plots. The seven study plots represented a vegetational and altitudinal gradient from mixed-shrub willow habitats to subalpine willow parks composed primarily of *Salix planifolia*. Changes in bird abundance were related to two major trends in habitat structure. Structural complexity was reduced at higher elevations as shrub species diversity, shrub size, canopy cover, and foliage density in the tall shrub layer declined (Finch 1987). Concomitantly, woody cover and foliage density in the surface and low shrub layers increased. Probably in response to these habitat changes, Wilson's warbler, white-crowned sparrow and Lincoln's sparrow, species that occupy sites with low, densely-foliated shrubs, reached peak abundance on the higher plots. Lincoln's sparrow was distributed over a greater range of plots usually at higher densities than other species, demonstrating greater flexibility in habitat use. Lincoln's sparrow was absent, however, from the lowest plot, possibly in response to reduction of preferred habitat due to elevational changes. Song sparrow, a species that selects tall shrub sites, had greatest densities on lower plots.

Characterizations of song sparrow-habitat relationships based on these results are only applicable for subalpine riparian habitats. Song sparrows are present at reduced densities in lowland cottonwood-willow habitat in the Rocky Mountains (Finch 1987). By excluding the cottonwood vegetational type from this analysis, data for describing the association between song sparrow abundance and habitat changes are incomplete. Gradient sampling in the other three bird species was probably adequate based on the lack of pronounced truncation in abundance trends (fig. 1).

Variability in Species Responses

In this study, each bird species responded differently to habitat variation. Strategies for managing single bird species in subalpine riparian habitats will therefore differ from those developed for groups of species. Effective management designs should rely on principles derived from bird-centered habitat features that significantly differ from random sites, either for each bird species or for the bird assemblage as a whole.

To produce an increase in Wilson's warbler and white-crowned sparrow numbers, habitats can be enriched if foliage density, cover, and abundance of subalpine willows are increased and coverage by open meadow and bare ground is reduced. Lincoln's sparrow is unrelated to most of the measured habitat features, achieving dominance on most shrub willow sites. Management schemes that emphasize subalpine avian specialists like Wilson's warbler (see Finch 1987) should enhance areas for Lincoln's sparrow as well. Lower-elevation riparian areas with larger shrubs are selected more heavily by song sparrows. Habitats within this range can be enhanced by managing for greater canopy cover, shrub size, and shrub cover than that which is randomly available. To improve habitat for all four species, efforts should concentrate on increasing shrub density and cover while emphasizing diversity in shrub height, crown diameter and dispersion, and surface cover of small shrubs and ground vegetation. Some of the damaging effects of livestock grazing on bird habitat can be mitigated if these recommendations are followed.

Sampling Scale

At the resolution level of the entire spectrum of plots, species densities were related to one or more vegetational features that changed over the elevational cline. Bird-habitat relationships models developed from these kind of data merely require population-monitoring along gradients of randomly-measured habitat. Within a local area, however, birds occupied habitat patches that differed from randomly-available habitat. In this study, each species selected sites within plots that differed from random sites for a variety of habitat features. Thus, sampling random habitat and bird abundance across many plots produced correlational information at a large scale, but the results do not apply for a specific locality.

Choice of sampling scale (e.g., single vs. multiple plots) and sampling intensity (e.g., random sampling only vs. bird-centered sampling) depends on study objectives and time and budget constraints. Site-specific studies using bird-centered data yield more detailed information on bird-habitat associations, but bird-centered data take much greater time and labor to collect, and results may only apply for a local area. I recommend sampling habitat at both bird-centered and random sites over a variety of vegetational types if managing a single species or guild in a specific locality is the goal. Such a sampling regime will provide more complete coverage of an animal's distribution and habitat requirements. Random sampling alone may be necessary if time and cost demands are prohibitive, or if the goal is to characterize habitat associations of large assemblages of birds in multiple habitats.

Acknowledgements

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The Coon Creek Wildlife Project: Effects of Water Yield Augmentation on Wildlife

Martin G. Raphael[1]

Abstract--The Coon Creek Water Yield Augmentation Pilot Project is a demonstration of timber harvest designed to increase water yield from a treated drainage compared to an untreated control. Of interest here are the effects of this pattern of timber harvest on bird and small mammal community structure, and on the distribution, habitat selection, and reproductive success of selected species. This paper describes preliminary results during the pretreatment phase of a longer-term study.

Subalpine forests of spruce, fir, and lodgepole pine are the largest and most valuable timber resources in Colorado and Wyoming (Alexander 1974), accounting for over 38% of the 13 million hectares (ha) of forest land and over 90% of sawtimber volume (USDA Forest Service 1980). These forests also provide habitat for 45 mammal, 93 bird, 2 reptile, and 5 amphibian species (Hoover and Wills 1984: Appendix A).

Subalpine forests in the central Rocky Mountains are harvested not only to provide timber, but also to increase water yield and other benefits (Alexander et al. 1983). The Rocky Mountain Region of the Forest Service proposed the Coon Creek Water Yield Augmentation Pilot Project (Bevenger and Troendle 1985) to (1) apply current best management practices to optimize water yield on an operational scale; (2) evaluate effects of current methods on yield, quality, and timing of water flow and timber production; and (3) test reliability of the state-of-the-art Subalpine Hydrological Model as a prediction tool on an operational scale.

The Coon Creek and Upper East Fork drainages of the Encampment River were selected for this project because they are large enough to expect a measurable effect; are of comparable size, aspect, elevation, and timber cover; and are commercially harvestable. Pre-treatment hydrologic data collection was initiated by National Forest personnel in 1983. Timber har- vest, consisting of 350 clearcuts averaging 3.8 acres (range 0.5-14.8 ac), is expected to begin in 1989 on the 3,987-acre Coon Creek watershed. The 2,252-acre East Fork watershed will remain uncut as a control.

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Our wildlife studies are designed to assess the impact of this water- yield harvest pattern on species composition and abundance of terrestrial wildlife. This study was begun in May, 1985 and will continue for at least three years following timber harvest. This report summarizes results of the first two years, emphasizing a comparison of vegetation between the two watersheds and wildlife populations among habitat types.

Study Area

The Coon Creek and Upper East Fork drainages are located in the Sierra Madre range in southern Wyoming. Elevations vary from 2,600 m to 3,300 m. Soils in both drainages vary between 50-150 cm deep and are well-drained. Mean yearly precipitation is about 100 cm, 70% of which occurs as snow. Forest cover is dominated by lodgepole pine (~60%) and Engelmann spruce/subalpine fir (40%). Pole stands (<23 cm d.b.h.) occur on 24% of the combined area of the two watersheds; sawtimber stands cover 72% and meadows or rock outcrops cover the remaining 4%.

Methods

Vegetation Sampling

Ninety sampling stations were established in each watershed (fig. 1) along N-S lines at 400-m intervals with 200 m between stations along each line. A single observer visited each sampling station in August, 1985 and measured basal area of each tree species using a metric Reloskop. Canopy cover was estimated from the average of four readings using a spherical densiometer. All snags >20 cm d.b.h. and 1.8 m tall

were counted within a 0.04-ha circular plot centered at the station; percent cover of shrubs, forbs, grasses, rocks, litter, and bare ground were visually estimated over the same 0.04-ha plot. Hard (class 1,2) and soft (class 3,4,5 [see Maser et al. 1979]) logs were also counted on each plot. Height and d.b.h. of one representative tree was measured at each station using a clinometer and metric d.b.h. tape.

All stands on each watershed were cruised by personnel of the Medicine Bow National Forest and assigned an old-growth rating based on canopy structure, d.b.h., tree height, snag size and density and log size and density. Possible scorecard values range from 0 (no old-growth characteristics) to 60 (maximum). Stand maps were used to associate a sampling station with the old-growth scorecard value for the stand in which the station was located.

Bird Community Structure

Three observers visited each sample station twice each year (for a total of six visits/station/year) from 13 June to 25 July 1985 and from 18 June to 23 July, 1986. At each visit, an observer recorded all birds and red squirrels heard or seen during a timed 10-min period and recorded the distance from the station center to the bird or squirrel. All counts were begun within 30 minutes after sunrise. Each observer visited 15 stations/day so that most counts were completed before noon.

Small Mammal Community Structure

To sample shrews, six pitfall traps were installed in a 2 x 3 grid (15-m spacing) centered on each station. Each pitfall trap was a 3-gal plastic bucket buried flush with the ground surface and covered by logs or bark. To capture other small mammals, observers placed two 50-cm Sherman livetraps within 2 m of each pitfall station.

Mammals were trapped over a 6-week period from 20 August through 26 September, 1985 and 5 August to 11 September, 1986. Observers checked traps daily during each of three, 10-day sampling sessions per year. All captured specimens were identified, sexed, aged, weighed, and checked for reproductive status (currently breeding or not). Any dead animals were assigned a permanent catalog number and either preserved in 70% ethanol (shrews) or frozen (everything else). Collected specimens were sent to the Museum of Natural History at the University of Kansas (shrews in 1985) or to the Denver Museum of Natural History (all else) for permanent deposit and identification.

Mountain Chickadee Reproduction

To estimate nesting success (clutch size, fledgling rate, recruitment) of the mountain chickadee, a secondary cavity nesting species, observers installed 100 Schwegler nest boxes

Table 1.--Mean values of vegetation attributes at vertebrate sampling stations[1] on the Coon Creek and East Fork watersheds.

Characteristic	Coon Creek	East Fork	Significance[2]
Basal area (m^2/ha)			
Lodgepole pine	17.4	16.5	N.S.
Engelmann spruce	7.1	8.9	N.S.
Subalpine fir	8.3	9.1	N.S.
Old growth score	35.1	36.6	N.S.
Canopy cover (%)	67.8	64.9	N.S.
Ave. tree height (m)	19.9	20.5	N.S.
Ave. d.b.h. (cm)	31.6	33.9	*
Snags/0.04-ha plot	1.9	2.0	N.S.
Percent cover			
Vegetation < 2.0 m tall	47.7	46.4	N.S.
Forbs	9.4	10.8	N.S.
Grasses	8.5	13.1	N.S.
Rock	5.6	1.7	***
Litter	79.4	81.1	N.S.
Bare Ground	1.3	1.3	N.S.
Hard logs/0.04 ha plot	3.0	1.5	***
Soft logs/0.04 ha plot	12.9	9.4	***
Cosine aspect	0.0	-0.1	N.S.
Slope (%)	24.2	24.7	N.S.
Stream proximity[3]	0.39	0.3	N.S.

[1]N = 90 stations per watershed.

[2]T-test results: N.S. = $P > 0.05$, *** = $P < 0.001$.

[3]Proportion of stations within 100 m of a permanent stream.

in each watershed in April (80 boxes) and October (20 boxes) 1985. Boxes were laid out in ten 4 x 5 grids, with 50-m spacing between boxes (fig. 1).

Boxes were checked at weekly intervals throughout the nesting period each year. If a nest was found, that box was checked more frequently until all young had fledged. Eggs and young were counted, and adults and young were weighed, measured, and banded with No. 0 Fish and Wildlife aluminum bands.

Marten Movements

The purpose of this study is to describe patterns of movement and habitat selection by marten before, during, and after timber harvest. Marten were trapped using up to 60 Tomahawk No. 205 livetraps placed intermittently throughout the study area. Traps were checked daily for periods ranging from 3-10 days, and were baited with cat food, meat scraps, feather lures, or fish.

Captured marten were sedated using an intramuscular injection of ketamine (0.05 cc/kg body weight), measured, weighed, and sexed. A permanent number was tattooed on the inside of the cheek, and a radio telemetry collar (various configurations) was fitted around the animal's neck. Each animal was retained inside the trap until recovery from the sedative was complete (usually 40 min). Collared marten were relocated twice per week from a fixed-wing aircraft.

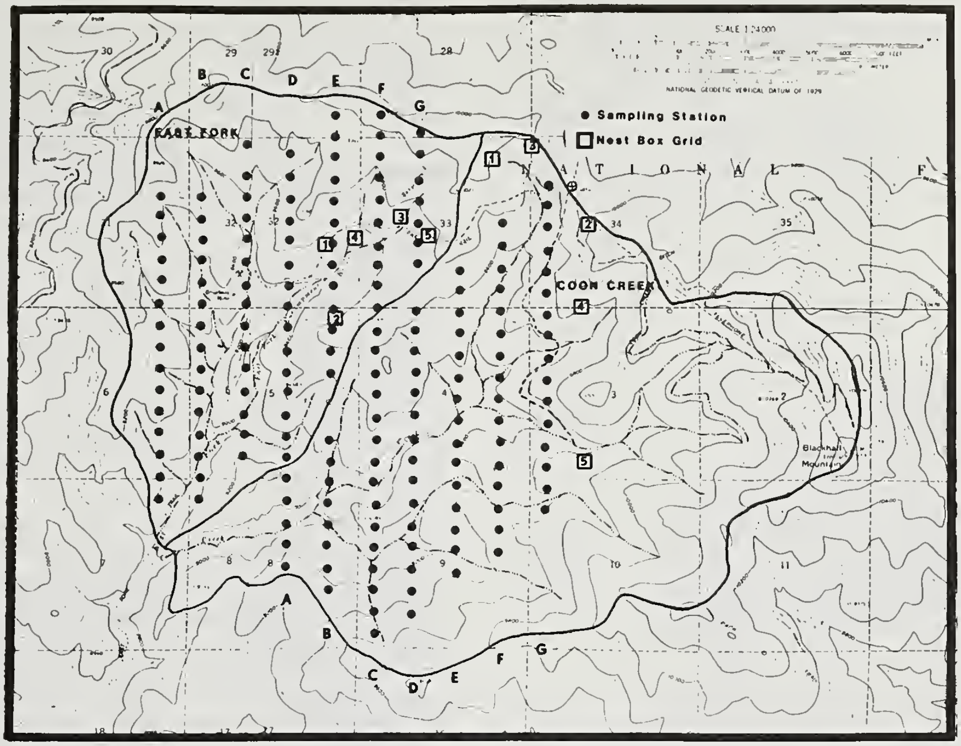

Figure 1.--Map of study area showing the Coon Creek and East Fork watersheds, sampling stations, and nest box grids.

Results

Vegetation

Vegetation characteristics were similar between the two watersheds (table 1). A discriminant analysis comparing mean values of basal area, d.b.h., height, canopy cover, and old growth score between the two watersheds was not significant (Chi-square = 10.3, DF = 7, $\underline{P}$ = 0.17). Slope, aspect, and stream proximity were also similar between the two watersheds (table 1).

Bird Community Structure

Observers sampled 41 bird species over both watersheds based on a total count of 14,897 observations. We observed 37 species on the Coon Creek watershed and 36 on the East Fork watershed. Those species that did not occur on both watersheds were rare (< 10 observations, total) and thus their occurrence on only one watershed was probably a matter of chance. Most species were equally abundant on the two watersheds, but 4 species (common raven, red-breasted nuthatch, mountain chickadee, ruby-crowned kinglet) were significantly more abundant on the East Fork and two (Clark's nutcracker, western flycatcher) were more abundant on Coon Creek (t - test, $\underline{P}$ < 0.05).

The mean abundance of six species differed significantly ($\underline{P}$ < 0.05) among the three primary timber types delineated on Stage II timber maps by Forest personnel (table 2). For those cases, the spruce-fir sawtimber type supported the greatest density, and as a result, also supported the greatest total density of birds (table 2).

Small Mammal Community Structure

We recorded at least 13 species of small mammals, all of which occurred on each watershed. We captured 2,428 individual animals during a total of 54,000 trap nights and recorded 755 observations of red squirrels during the bird counts (table 3). The most abundant small mammal was Gapper's Red-backed Mouse (1,203 individuals) followed by shrews (788) and Deer Mouse (131). The mean capture rate of shrews, Gapper's red-backed mouse, and western jumping mouse differed significantly among timber types, and all of these species were most abundant in the spruce-fir sawtimber sites (table 3). Mean capture rate of Gapper's red-backed mouse was greater in the Coon Creek watershed and the capture rate of the deer mouse was greater in the East Fork watershed; all other species were captured at nearly equal rates on the two watersheds.

Ecological Indicator Species

Several of the birds and mammal species studied are listed as ecological indicators by the Medicine Bow National Forest

Table 2.--Mean density (birds/100 ha) of birds among timber types on Coon Creek and East Fork watersheds, 1985-1986.

Bird species	Timber type: Lodgepole pine pole (n = 36)	Lodgepole pine sawtimber (n = 76)	Spruce/fir sawtimber (n = 59)
Sharp-shinned hawk Accipiter striatus	0	+	0
Cooper hawk Accipiter cooperii	+	0	+
Northern Goshawk Accipiter gentilis	+	0	0
Red-tailed Hawk Buteo jamaicensis	0	+	+
Northern Pygmy-Owl Glaucidium gnoma	+	0	0
Boreal Owl Aegolius funereus	0	0	+
Broad-tailed Hummingbird Selasphorus platycercus	7	11	8
Williamson's Sapsucker Sphyrapicus thyroideus	1	4	4
Downy Woodpecker Picoides pubescens	0	+	+
Hairy Woodpecker Picoides villosus	+	+	+
Three-toed Woodpecker Picoides tridactylus	+	1	2
Northern Flicker Colaptes auratus	1	1	1
Olive-sided Flycatcher Contopus borealis	0	+	+
Western Wood-Pewee Contopus sordidulus	0	0	+
Western Flycatcher Empidonax difficilis	3	3	6
Gray Jay Perisoreus canadensis	35	32	39
Clark's Nutcracker Nucifraga columbiana	1	2	1
Common Raven Corvus corax	+	2	11
Mountain Chickadee Parus gambeli	50	52	63
Red-breasted Nuthatch Sitta canadensis	2	2	2
Brown Creeper Certhia americana	8ab	9a	16b
American Dipper Cinclus mexicanus	0	0	+
Golden-crowned Kinglet Regulus satrapa	29a	33a	69b
Ruby-crowned Kinglet Regulus calendula	49	44	50
Mountain Bluebird Sialia currucoides	0	+	0
Townsend's Solitaire Myadestes townsendi	+	2	+
Swainson's Thrush Catharus ustulatus	2ab	1b	3a
Hermit Thrush Catharus guttatus	21	22	25
American Robin Turdus migratorius	52a	50a	68b
Warbling Vireo Vireo gilvus	+	0	+
Yellow-rumped Warbler Dendroica coronata	198	200	196
Wilson's Warbler Wilsonia pusilla	0	0	+
Chipping Sparrow Spizella passerina	+	+	+
Lincoln's Sparrow Melospiza lincolnii	7a	3a	19b
Dark-eyed Junco Junco hyemalis	143	153	164
Pine Grosbeak Pinicola enucleator	11	13	15
Cassin's Finch Carpodacus cassinii	4	4	4
Red Crossbill Loxia curvirostra	13	22	15
White-winged Crossbill Loxia leucoptera	0	+	0
Pine Siskin Carduelis pinus	70a	70a	90b
Evening Grosbeak Coccothraustes vespertinus	+	+	+
Total density	710a	738a	864b

[1]Pairs of means with same superscript letter did not differ significantly (Duncan multiple-range test, P < 0.05). Superscripts were not included if none of the means differed significantly.

[2]+ indicates mean density < 1 bird/100 ha.

Table 3.-- Small mammal capture rates on the Coon Creek and East Fork watersheds, 1985-86.

Species	No. captured	Mean capture rate (N/300 trapnights)[1]: Lodgepole pine pole	Lodgepole pine sawtimber	Spruce/fir sawtimber
Shrews[2] (Sorex spp.)	788	2.72[a]	3.87[a]	6.09[b]
Water Shrew (Sorex palustris)	7	0	0.08	0.02
Least Chipmunk (Eutamias minimus)	46	0.42	0.14	0.33
Uinta Chipmunk (Eutamias umbrinus)	104	0.69	0.67	0.39
Golden-mantled Ground Squirrel (Spermophilus lateralis)	7	0.06	0.05	0.02
Red Squirrel[3] (Tamiasciurus hudsonicus)	7	60.4	46.0	0.2
Deer Mouse (Peromyscus maniculatus)	131	0.58	0.71	0.63

(continued)

Table 3.--(continued).

Species	No. captured	Mean capture rate (N/300 trapnights)[1] Lodgepole pine pole	Lodgepole pine sawtimber	Spruce/fir sawtimber
Gapper's Red-backed Mouse (Clethrionomys gapperi)	1,203	4.86[a]	6.01[ab]	8.37[b]
Heather Vole (Phenacomys intermedius)	2	0	0.03	0
Montane Vole (Microtus montanus)	14	0.06	0.07	0.08
Long-tailed Vole (Microtus longicaudus)	6	0	0.04	0.05
Western Jumping Mouse (Zapus princeps)	78	0.03[a]	0.42[ab]	0.69[b]
Ermine (Mustela erminea)	5	0	0.04	0.02

[1]See footnote 1, table 2, for explanation of letter superscripts.

[2]Identification pending analysis by taxonomic experts.

[3]Results presented for counts made during bird censuses and are expressed as number/100 ha.

(table 4). Three are indicators of late seral vegetation, but only one of these, Gapper's red-backed mouse, was actually more abundant in stands rated most highly for old-growth conditions (fig. 2). Two species are listed as indicators of early seral conditions. One of these was too rare to assess adequately; the other (western jumping mouse) was most abundant in wet, grassy habitats but occurred in both late and early seral stages and was most abundant at sites with large-diameter, tall trees (table 4).

Mountain Chickadee Reproduction

Of the 160 nest boxes available to chickadees during each of two nesting seasons, only four were used each year. Each of these eight nests was 100% successful. Observers banded all but one adult and one nestling associated with nests. Low use of nest boxes during the first years following installation has been reported by other researchers (Brawn and Balda 1983); occupancy is expected to rise in succeeding years. However, an additional 180 boxes were added, one at each vertebrate sampling station, to increase box availability and create a more dispersed distribution of boxes.

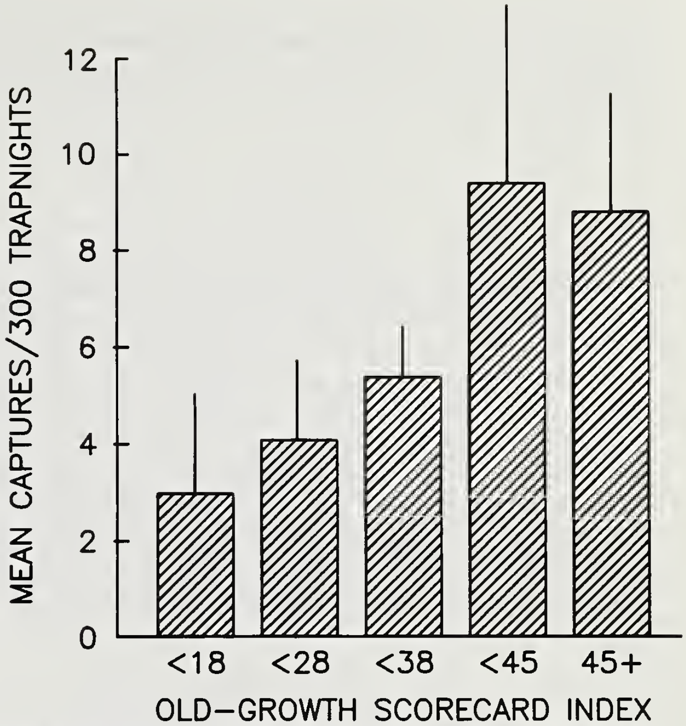

Figure 2.--Relative abundance (mean capture rate) of southern red-backed vole in relation to old-growth scorecard value. Vertical lines indicate upper 95% confidence of means.

Pine Marten Movements

During the period from 30 May 1985 through 30 April 1987, observers captured 23 marten and fitted radio telemetry

Table 4.--Correlations[1] of habitat characteristics associated with abundance of ecological indicator species (USDA 1985) sampled in community studies, 1985-1986.

Ecological indicator species	Old-growth score[2]	Stream presence	Basal area pine	Basal area spruce	Basal area fir	d.b.h.	Height
Gapper's Red-backed Mouse[3]	0.27	0.24	-0.50	0.42	0.28	0.24	0.38
Long-tailed Vole[4]							
Western Jumping Mouse[4]		0.39	-0.22	0.27		0.25	0.30
Hairy Woodpecker[3]							
Ruby-crowned Kinglet[3]					0.20		

[1]Pearson correlation coefficients are listed in table. Only significant ($P < 0.05$, n = 167) values are listed.

[2]Numerical scorecard rating of old growth conditions, as determined by Medicine Bow National Forest personnel.

[3]Indicator of late-seral conifer vegetation.

[4]Indicator of early seral vegetation.

collars on 20 of them. These animals have been relocated from 1 to 69 times for a total of 521 locations of all collared animals. The distribution of some of some of these animals is illustrated in figure 3.

Conclusion

All of these results are preliminary but they show that, in general, the vegetation structure and vertebrate community of the two watersheds are quite similar. Thus, these watersheds seem to be ideal for the longer term comparative study before, during, and after timber harvest. A number of species reach peak abundance in mature conifer sites, and these species are most likely to decline as timber is harvested. The greatest unknowns at present are (1) which species will benefit from the creation of early seral habitats, and (2) whether fragmentation of the Coon Creek watershed will result in unpredicted changes in abundance of species favoring late-seral stages.

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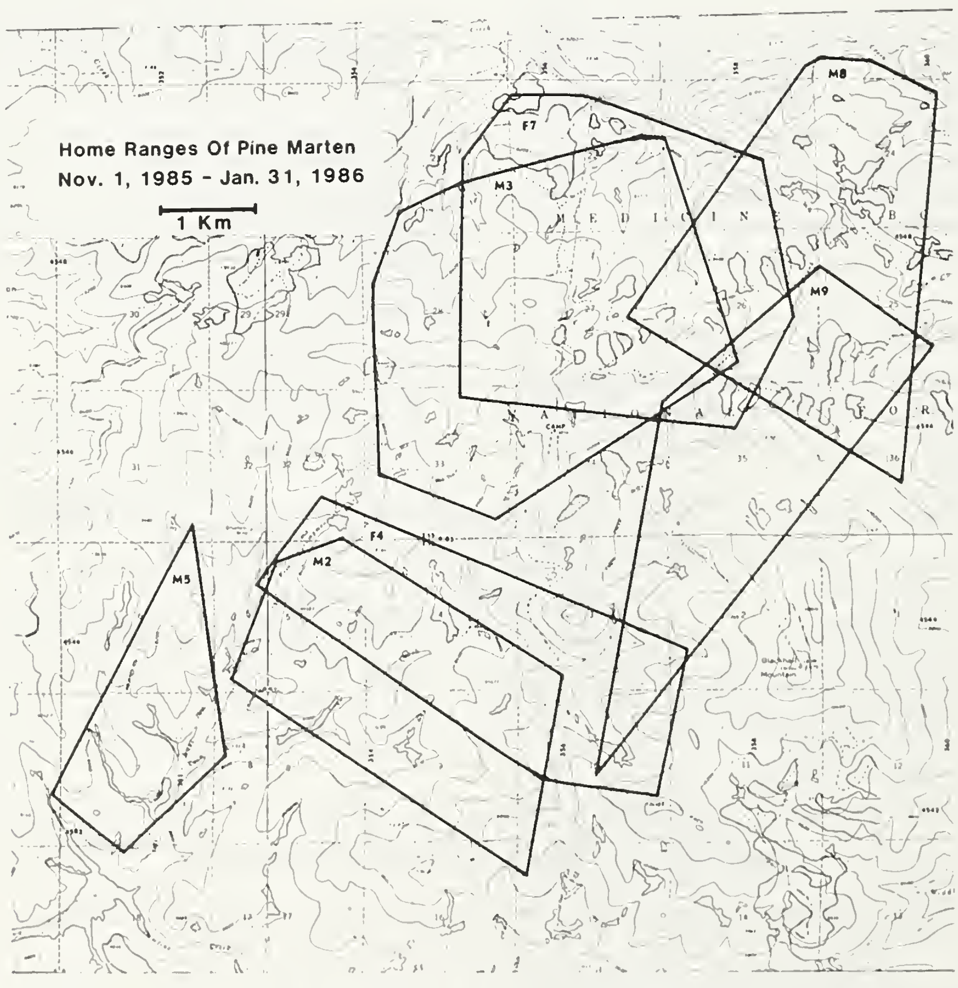

Figure 3.--Distribution of marten, November-January 1985/86 in vicinity of Coon Creek study area.

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Growth Efficiency, Leaf Area, and Sapwood Volume in Subalpine Conifers

Michael G. Ryan[1]

Abstract--Growth efficiency (stemwood produced per unit leaf area) estimates the ability of a tree to convert light energy into wood, and indicates carbon allocation processes. Maintenance respiration of woody tissues may cause observed patterns in growth efficiency decline in subalpine conifers.

Carbon fixed in photosynthesis provides the raw material not only for stem growth, but also for growth of leaves, branches, coarse and fine roots, and for the maintenance of living tissue (Kaufmann et al., this volume). However, not all tree parts have an equal chance of receiving this newly fixed carbon--maintenance of living tissue and the growth of fine roots and leaves have a higher priority than stem growth (Waring and Schlesinger 1985). The amount of carbon fixed, though, is related to the amount of leaf area (Linder 1985), the productive machinery of the tree. Since stemwood production has a low priority for fixed carbon, it can be a sensitive measure of the use of carbon by other tree parts. Therefore, growth efficiency (stemwood production per unit of leaf area) can indicate changes in the pattern of carbon allocation within the tree (Waring 1983).

Growth efficiency declines with increased tree age much faster for lodgepole pine (*Pinus contorta* var *latifolia* Engelm.) than for Engelmann spruce (*Picea engelmannii* Parry or subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) in Colorado subalpine forests (Kaufmann and Ryan 1987). Because growth efficiency can be an indicator of carbon allocation, the more rapid decline of growth efficiency for lodgepole pine compared with the other conifers suggests that carbon allocation patterns vary with tree size, species, and shade tolerance.

The change in growth efficiency patterns for these conifers over time may be related to changes in the balance between photosynthetic and respiring tissue. These tree species differ in the amount of leaf area supported per unit of conducting sapwood area, with lodgepole pine supporting much less leaf area than the other two conifers (Kaufmann and Troendle 1981). Since the sapwood of these species contains about 6% live parenchyma ray cells (Panshin and de Zeeuw 1970) and the volume of sapwood increases considerably with tree size, sapwood volume may be a reasonable predictor of maintenance respiration demand. Since photosynthesis per unit of leaf area is similar for the three species (Smith 1985), carbon assimilation should be proportional to leaf area. Therefore, trees in species with a low ratio of leaf area to sapwood should have a much greater relative respiratory loss of carbon than trees of species with a high ratio of leaf area to sapwood area. Differences in maintenance respiration should change the carbon available for stem growth and therefore change growth efficiency.

The objectives of this paper are (1) to present some background information on stem respiration in trees, (2) to examine evidence which suggests that maintenance respiration of woody tissues, particularly sapwood, increases as trees grow larger, and (3) to propose reasonable tests of the hypothesis.

Background

Respiration can be divided into two functional components: construction (growth) respiration and maintenance respiration (McCree 1970). Growth respiration refers to CO_2 evolution from processes generating energy for the synthesis of plant dry matter. Maintenance respiration is the CO_2 evolution from maintenance processes within the cell including protein turnover, the maintenance of ion and metabolite gradients (including membrane integrity), and physiological acclimation to a changing environment (Penning de Vries 1975). While the two processes may produce distinct end products, the carbon dioxide evolved is not biochemically distinct.

Growth respiration is proportional to the growth increment (dW/dt), while maintenance respiration is a function of the mass of living tissue (W) and temperature (T). Total respiration may then be expressed as:

$$R = a * dW/dt + b * f(W, T) \quad [1]$$

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where a and b are partitioning coefficients (Landsberg 1986). Growth respiration is independent of temperature, while maintenance respiration increases exponentially with temperature (Landsberg 1986).

Maintenance respiration may be very important for trees because of the large amount of respiring biomass in the stem, roots, and branches, and the sensitivity of this process to temperature. Because maintenance respiration is sensitive to temperature and tree size, knowledge of respiration can help explain differences in tree growth among the widely varying sites in the subalpine. Additionally, information about maintenance respiration should be useful in predicting the results of regional climatic changes on tree growth and species composition.

Stem and branch respiration is an important component in the carbon balance of trees, but has received little attention. However, a few studies have shown that respiration by woody tissues utilizes a large fraction of the annual photosynthetic production, particularly for larger trees. For example, Benecke and Nordmeyer (1982) estimated that 23% of annual production was respired by stems in a 40-year-old subalpine lodgepole pine stand. In contrast, smaller trees use less carbon for maintenance respiration. Stem respiration used 7% and branch respiration used 28% of annual photosynthetic production in a 14-year-old loblolly pine stand (Kinerson 1975). Linder and Troeng (1981) found that 5% of annual production was used for stem and branch respiration of a 20-year-old Scots pine tree. Because the annual carbon balance is difficult to quantify, these estimates suggest only the magnitude of the respiration fraction, and do not separate growth and maintenance respiration.

Stem respiration, then, can be an important component of the tree's carbon balance, and our knowledge of stem respiration is limited. Separation of stem respiration into growth and maintenance components may aid in understanding tree growth patterns, because of the sensitivity of the maintenance component to temperature. Little is known about the magnitude of these two components, the contribution from various tissues, and changes in carbon allocation to growth and maintenance respiration of stems with stand development.

Observations from Current Research

My research is focused on exploring patterns in carbon allocation for subalpine conifers and examining the impact of maintenance respiration on growth efficiency. In addition to the work on growth efficiency and age presented in Kaufmann and Ryan (1987), I have explored the question of growth efficiency decline using several approaches. These include (1) examining patterns of leaf area and sapwood volume development for subalpine conifers, (2) studying patterns in growth efficiency for lodgepole pine growing under two different temperature regimes, and (3) comparing growth efficiency of similar species in very different climatic regimes. These preliminary results suggest that the observed patterns in growth efficiency may be related to maintenance respiration of woody tissues (particularly sapwood).

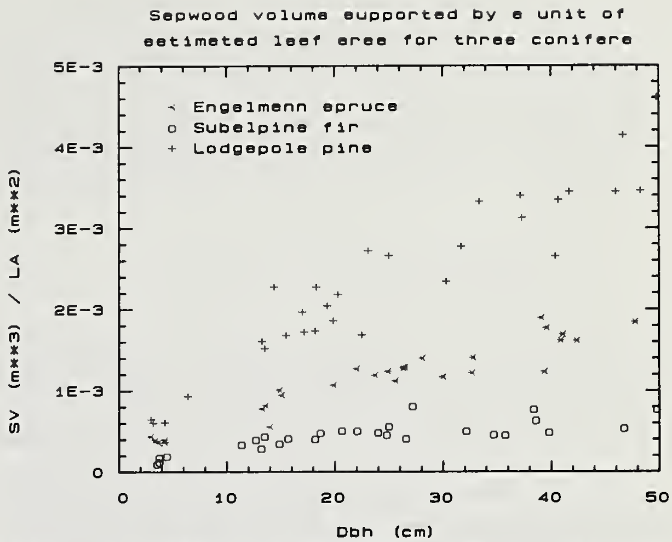

Figure 1.--Actual sapwood volume supported (SV) by a unit of estimated leaf area (LA) for three subalpine conifers as a function of diameter (d.b.h.).

Leaf Area and Sapwood Volume Development

I measured sapwood volume on 30 trees each of lodgepole pine, Engelmann spruce, and subalpine fir, using stem sections and standard mensurational techniques for volume determination.[2] For each of the sample trees, leaf area was estimated from equations given in Kaufmann and Troendle (1981). The ratio of actual sapwood volume to estimated leaf area increased much more rapidly with tree size for lodgepole pine than for spruce or fir (fig. 1). If carbon assimilation is proportional to leaf area, then the use of carbon by sapwood in maintenance respiration increases with the ratio of sapwood volume to leaf area. Therefore, lodgepole pine should show the strongest decline in growth efficiency with increasing tree size, since it should have the largest demand for maintenance respiration.

Sapwood volume equations[2] were used to estimate sapwood volume for the data presented in Kaufmann and Ryan (1987). Volume growth and sapwood volume were both divided by estimated leaf area to reference these variables to a comparable level of productive capacity. Although I believe that a reasonable interpretation of the data is possible using such an approach, autocorrelation may complicate interpretation of the resultant patterns.

Plots of growth efficiency (volume growth per unit estimated leaf area) versus sapwood volume per unit estimated leaf area show a strong negative relationship for lodgepole pine, and a constant growth efficiency for spruce and fir (figs.

[2]Ryan, M. G. 1987. Sapwood volume equations for three subalpine conifers. Manuscript in preparation.

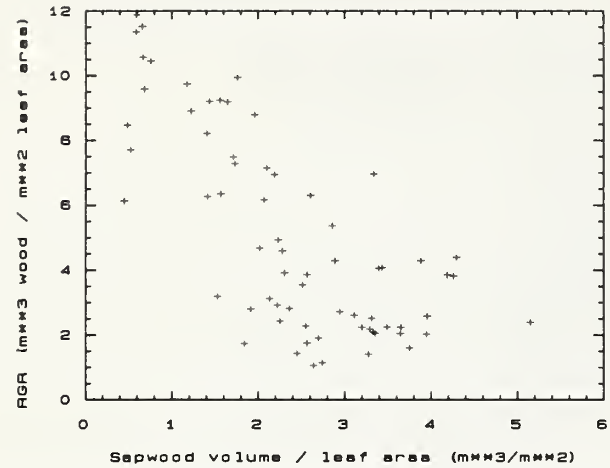

Figure 2a.--Growth efficiency (RGR, volume growth per unit of estimated leaf area) versus sapwood volume supported per unit leaf area for lodgepole pine.

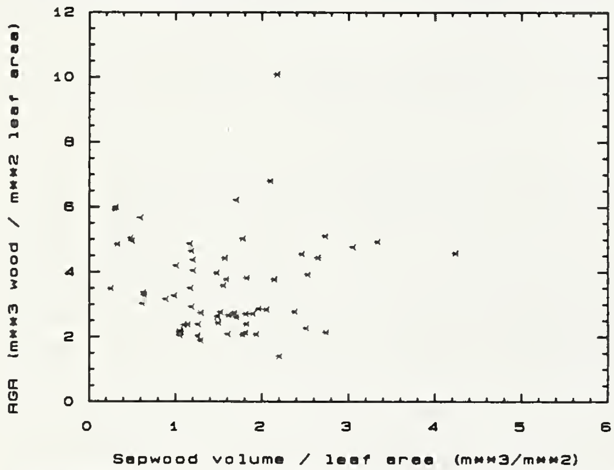

Figure 2b.--Growth efficiency (RGR, volume growth per unit of estimated leaf area) versus sapwood volume supported per unit leaf area for Engelmann spruce.

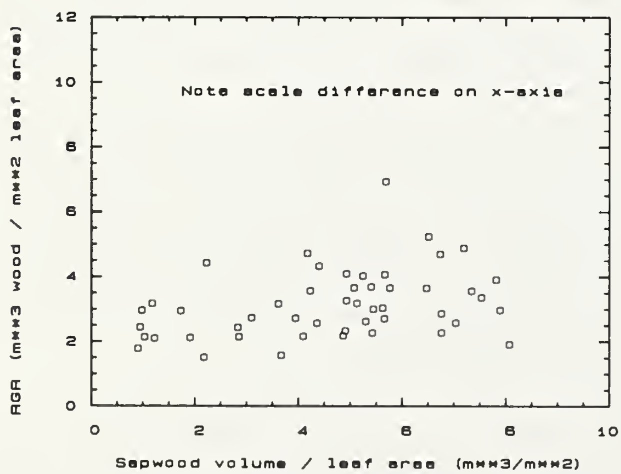

Figure 2c.--Growth efficiency (RGR, volume growth per unit of estimated leaf area) versus sapwood volume supported per unit leaf area for subalpine fir.

2a, 2b, 2c). These patterns indicate that relative growth rate may be related to sapwood volume for lodgepole pine, and that the pattern of growth efficiency decline is consistent with the relationships presented in figure 1.

Growth Efficiency Decline Under Two Temperature Regimes

I examined the relationship between growth efficiency, leaf area, and sapwood volume for lodgepole pine stands of different ages growing at two different elevations.[3] Even-aged stands of 40, 60, and 240 years in age were sampled at 2,800 m in elevation, and stands of 40, 75, and 240 years in age were sampled at an elevation of 3,200 m. All other physiographic characteristics were similar for the 6 stands: slopes were less than 10%, aspects were between 315 and 360 degrees, and *Vaccinium scoparium* was the dominant understory plant. Additionally, stand factors (basal area, leaf area, crown competition, stems per hectare) were similar among all stands. Of course, these stand factors changed somewhat with stand age, in response to normal growth.

These stands should have an average temperature regime that differs by 4 C, based on the dry adiabatic lapse rate applied to the 400-m elevation difference. Since maintenance respiration for a given live biomass is strictly a function of temperature (Landsberg 1986), the carbon used in maintenance respiration should be lower for the cooler (high elevation) stands. Because the 3,200-m stands use less carbon for respiration, growth efficiency should decline less rapidly than for the 2,800-m stands, if carbon assimilation and fine-root turnover remain constant.

The rate of decline in growth efficiency for these stands appears to be related to sapwood volume (fig. 3), but there is no difference with elevation. Actual measurements at the sites confirm the 4 C difference in temperature during the growing season. The lack of difference in growth efficiency decline between elevations suggests that there may be compensating mechanisms in carbon allocation processes. Both carbon assimilation and fine-root turnover may offset changes in maintenance respiration demand. Much more work is needed to characterize the carbon budget for these stands.

Growth Efficiency Decline in Two Regions

I compared growth efficiency for aspen and lodgepole pine stands growing in Colorado with stands of aspen and jack pine (a species very similar to lodgepole) growing in the north-central United States. These two locations doubtless have many differences, but the major differences are likely to be the length of the growing season and the temperature regime

[3]Ryan, M. G. Leaf area and sapwood volume development in subalpine lodgepole stands: the relationship between carbon production and consumption. Manuscript in preparation.

during the growing season. The Colorado sites are characterized by shorter growing seasons and cooler night temperatures.

A yield-table program for even-aged stands in the Rocky mountains (RMYLD, Edminster (1978)) was used to estimate stem volume growth for stands of aspen and lodgepole pine. The simulations were run using a site index of 21 m/80 y and "non-limiting" conditions; that is, I chose a relatively low density (740 per ha) stocking level so that trees were free to grow, and predicted density dependent mortality was minimized. Aspen volume growth for the north-central states was calculated from yield tables given in Perla (1977) using a site index of 21 m/50 y. Volume growth for jack pine in the north-central states was calculated from information in Benzie (1977). Leaf area was calculated from basal area using equations in Kaufmann et al. (1982); leaf area for jack pine was calculated using lodgepole pine equations. Nine 10-year projection periods were used for RMYLD simulations and six 10-year projection periods were used from the north-central yield tables.

These regions have very different productive capabilities (based on site index), with the north-central sites having a much higher potential growth. Since the productive capabilities are so different between the regions, I could not model stand growth using the same site indices. Therefore, I selected the site indices of 21 m/80 y for the Rocky Mountains and 21 m/50 y for the north central because they represented very productive sites relative to others in the region.

Growth efficiency declines much more rapidly for stands in the north-central United States than in the Rocky Mountain region (fig. 4). The difference in productive capacity is very evident for the aspen stand, but production rapidly approaches that found in the Rocky Mountains as the living biomass increases. Relative growth rate for jack pine in the north central is initially similar to that in the Rocky Mountains but it declines more rapidly.

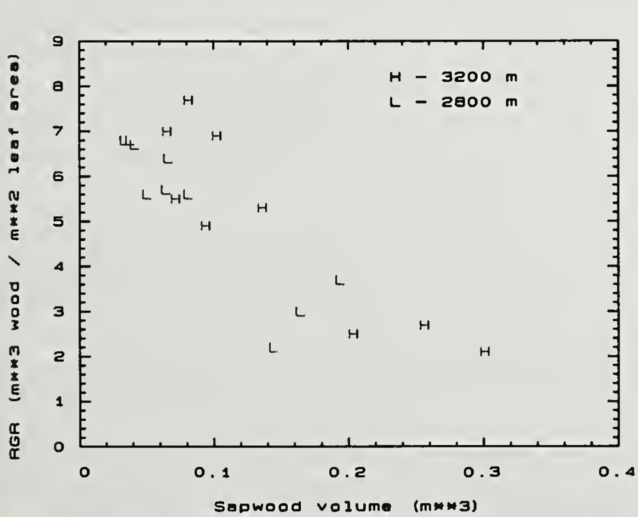

Figure 3.--Mean growth efficiency per tree versus sapwood volume for 6 lodgepole pine stands (3 plots per stand) at two elevations.

Additionally, there are pronounced differences in longevity between the two regions. Aspen in the north central states rarely lives beyond 60 years, while the life expectancy in the Colorado Rockies is almost double that. Since one of the major environmental differences between these sites is the warmer temperatures of the north-central site, maintenance respiration could explain these differences.

Conclusions and Recommendations

These preliminary observations indicate that carbon allocation patterns vary widely among subalpine conifers. Maintenance respiration of woody tissues may explain the observed patterns of growth efficiency and carbon allocation, but additional work is needed to fully understand the processes. The hypothesis that maintenance respiration of woody tissues accounts for an ever-increasing share of the tree's carbon as the tree grows should be tested directly by: (1) estimating growth and maintenance respiration of various woody tissues and relating respiration to live cell content, and (2) predicting growth efficiency patterns for stands from information on leaf area and sapwood volume development--then comparing these predictions to field measurements. Work with maintenance respiration may allow us to predict the effects of large scale temperature changes on tree growth and longevity.

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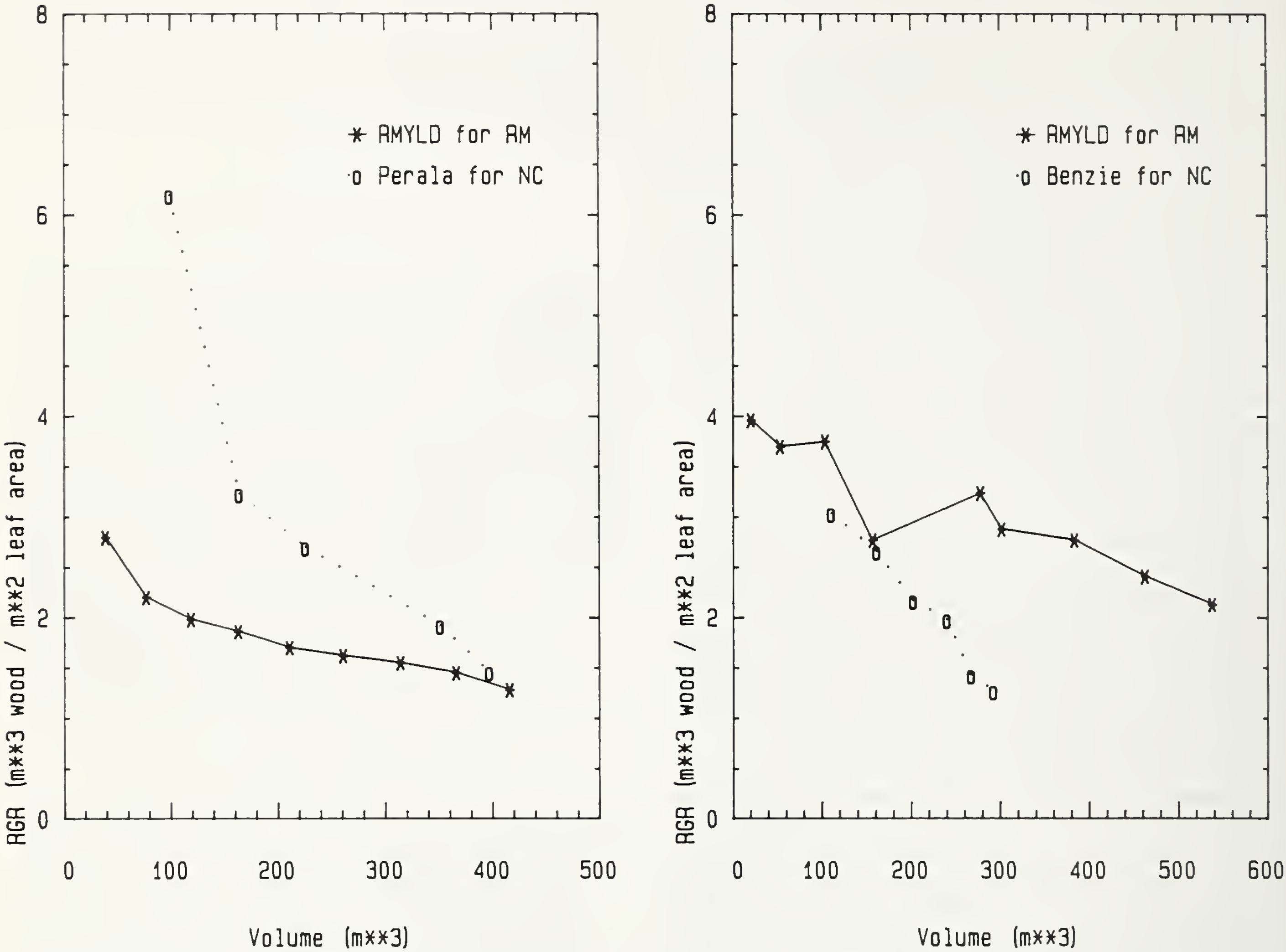

Figure 4.--Growth efficiency versus stand volume for aspen in the Rocky Mountains and aspen in the north-central states and for lodgepole pine in the Rocky Mountains and jack pine in the north central states.

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Observations of Oversnow Flow in Subalpine Meadows of Colorado

Richard Kattelmann[1]

Abstract--Oversnow flow occurs when snowmelt runoff saturates snowpacks and results in formation of channels at the snow surface. Where these channels extend through the snowpack to the soil surface, localized soil erosion may be much greater than commonly expected under snowmelt conditions. Oversnow flow and associated soil erosion were observed at several locations in Colorado.

Oversnow Flow

Snowmelt percolates through the unsaturated bulk of the snowpack to a saturated zone overlying the soil surface. Snowmelt water may then infiltrate into the soil or travel downslope over the soil, where it accumulates the contributions of other portions of the snow cover. Water flowing downslope both through and over the soil concentrates in topographic depressions and eventually in small stream channels. Where midwinter streamflow is too low to maintain an open channel, the stream channels are usually blocked by ice and snow at the onset of spring snowmelt. If the melt rate increases gradually, then the permeability of the ice and snow in the channels may increase quickly enough to accommodate the increasing flows. Over time, the ice and snow melt from frictional heating, and the channel opens up under the snow.

Alternatively, the permeability of ice and snow in the channels and any open channel capacity may be insufficient to pass all of the runoff generated by rapid snowmelt. The saturated volume of the snowpack around the stream channel increases until all of the water received at a point can be transported downstream. In many cases, a balance in flow is not reached until the entire depth of the snowpack is saturated. When the water table reaches the snow surface, water begins to flow freely downhill as oversnow flow.

This open channel flow confined by saturated snow can be termed oversnow flow. It appears to be a highly localized and transitory phenomenon occurring only under certain combinations of snowpack, meteorologic, and topographic conditions. But it can be important locally because of its ability to increase peak streamflows and sediment delivery (Sturges 1975). Oversnow flow occurs where water inputs to the snowpack in a topographic depression exceed the capabilities of undersnow stream channels and Darcian flow through the snowpack to transport water downslope. It may be considered analogous to saturation overland flow (Sturges 1975). A special type of oversnow flow occurs when a stream is suddenly blocked and water flows over unsaturated snow for a few minutes before infiltrating into the snow cover.[2]

Oversnow flow has been described in detail for the big sagebrush country of south-central Wyoming (Sturges 1975) and mentioned in relation to lake overflow and channel development during spring breakup in the High Arctic (e.g., Woo 1980, Woo and Sauriol 1980) and Antarctic (Birnie and Gordon 1980). Otherwise, only a few topics related to saturated snow appear in the hydrology literature. Fully-saturated snowpacks have been noted in subarctic Quebec (Granberg 1979). Macropores in snow have been identified as open conduits within snowpacks which permit rapid drainage of saturated zones (Kattelmann 1985). Supraglacial streams occur on the firn and ice of temperate glaciers and have been studied in relation to channel development processes (e.g., Dozier 1976, Knighton 1981, Parker 1975).

Saturation of snow with water can result in slushflows when an entire mass of slush is set in motion (Washburn and Goldthwaite 1958). They are a common feature of northern latitudes (e.g., Luckman 1977, Nyberg 1985, Onesti 1985) and a serious hazard in Norway (Hestnes 1985). Many slushflows probably begin where oversnow flow is occurring. While saturated snow is known to have inherently low strength, not all slush accumulations become slushflows. Slushflows have great erosive power (Nyberg 1985) and can be a very effective geomorphic agent (Luckman 1977).

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This paper describes observations of oversnow flow in subalpine meadows of central Colorado during two spring melt periods and suggests possible consequences of such flow.

Field Observations

The primary study area was at Shrine Pass (3350 m elevation) near Vail Pass on Interstate Highway 70. Near the pass, Turkey Creek begins in a meadow with a slope of 2^{o} to 3^{o} to the north-northwest, and West Tenmile Creek begins in a meadow with similar slope on the south side. The snowpack is usually about 1 to 2 m deep at the typical onset of melt in mid-May. Streamflow is measured by the U.S. Geological Survey in both streams, but the gaging stations are located too far downstream to reveal anything about flow conditions in the headwaters. Oversnow flow was also observed at the study site on June 3 and 16-17, 1979 and in mid-June, 1980, as well as near Loveland Pass (3650 m), Trail Ridge (3700 m), Tennessee Pass (3200 m), and Independence Pass (3700 m) in June and July 1979. Such flow has also been seen by the author on numerous occasions in the Sierra Nevada of California.

Oversnow channels commonly began in zones of obviously saturated snow 3 to 7 m across. The channels took form 5 to 20 m downslope of the uppermost saturated snow (fig. 1). The snow channels ranged from 10 to 150 m long before the water entered an exposed stream channel. All incised channels observed in Colorado were from 0.2 to 0.8 m wide and 0.3 to 1 m deep. The form of the channels changed markedly over the course of a day as the channels adjusted to changing discharge and alternate erosion and clogging with displaced snow. The channels tended to meander except where they became deeply incised. These snow channels were not always found directly above their earthen counterparts.

Surface velocities of 0.1 to 0.6 m/s were measured. Estimated discharge in the surface channels at various points and times ranged from 0.01 to 0.1 m^3/s. Snowpits were excavated at 2-m intervals away from the stream to determine the depth and extent of saturated snow (fig. 2). On low-gradient side-slopes, saturated snow was found only a few centimeters below the snow surface and for more than 10 m away from the channels.

The bed of the incised channels intermittently contacted the soil surface. Downstream of such points of contact were large accumulations of sediment (fig. 3). Occasionally, the water in a short reach was quite turbid. Sediment was deposited where snow channels ended because of the reduction in water velocity. Sediment was also found where oversnow flow ceased and water infiltrated into snow in areas that lacked large conduits or macropores.

Figure 1.--Oversnow flow channels begin in broad zones of saturated snow.

Possible Consequences of Oversnow Flow

Water flow through saturated snow has few external effects so long as it remains below two critical thresholds. At the extreme, if water accumulates to the point where the structural integrity of the snow mass is exceeded, then a slushflow is released. A less spectacular threshold is the saturation of the full depth of the snowpack where oversnow flow begins. At this point, resistance to flow decreases sharply and velocity increases. As the surface channel cuts into the snowpack through both mechanical and thermal erosion, more water drains into the channel from the sides, adding to the overall stream power.

The concentration of water in a highly efficient, low-friction channel results in great erosive potential wherever it reaches the underlying soil. Because of the rapidly changing nature of the snow channel, erosion can occur at several locations during the few days of intense oversnow flow. One factor that limits the duration of oversnow flow is breakup of the snowpack down to the soil surface. Extensive soil displacement was noted at the sites of oversnow flow observed in Colorado. Substantial bank cutting, very high suspended sediment concentrations, and thick channel deposits have been noted in connection with oversnow flow in Wyoming (Sturges 1975).

Erosion by oversnow flow usually occurs in meadows and along stream courses. Such areas are of special concern because they are sensitive to forest management activities. The occurrence of oversnow flow-induced erosion may help explain soil disturbance found to be in excess of what is normally expected under snowmelt runoff conditions. Knowledge of the potential effects of oversnow flow could also improve the effectiveness of meadow restoration, gully control, roaddrainage, and channel stability maintenance efforts.

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Figure 2.--Snowpits excavated below points of infiltration showed the extent of water-saturated snow.

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Figure 3.--The areas where the snow channels broke up and the water slowed down were covered by sediment deposits.

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Stormflow Responses to Forest Treatments on Two Arizona Mixed Conifer Watersheds

Alden R. Hibbert and Gerald J. Gottfried[1]

Abstract--Forty years of hydrological records from the North and South Forks of Workman Creek were analyzed to estimate the effects of several treatments on stormflow volumes and peaks. Summer stormflows and peaks increased exponentially with size of storm after each treatment. Although percent changes were large, actual increases were very small. Winter stormflow increases were smaller on a percent basis but were larger In volume.

Water yield improvement has been the major emphasis of forest hydrology in the arid Southwest, where the demand is great for water. However, precipitation varies greatly from year to year and large amounts of runoff may be generated by individual storms. In recent years, several large winter storms have generated damaging floods which have raised fears of dam failures in the main valley population centers.

These events have created an interest in the effects of forest management practices on both winter and summer stormflow volumes and peak flow rates. It is well known that water yields can be increased by reducing forest cover (Rich and Gottfried 1976, Brown and et al. 1974, Baker 1986). However, it is not known if stormflows are increased proportionately to nonstorm (base) flows, since little work has been done on individual stormflows.

Mixed-conifer forests occupy 322,500 acres in Arizona, and approximately 2 million acres in the entire Southwest, including southwestern Colorado. The 40-year hydrological record on the Workman Creek watersheds provides an excellent opportunity to describe and analyze the effects of several forest management treatments on stormflow volumes and peak flow rates.

STUDY AREA

Workman Creek is within the Sierra Ancha Experimental Forest, approximately 30 miles north of Globe in central Arizona. The three experimental watersheds are North Fork (248 acres), Middle Fork (521 acres), and South Fork (318 acres). Elevations range from 6645 to 7789 ft.

The climate at Workman Creek is characterized by cold, moist winters; warm, dry springs and falls; and by warm, moist summers. The average annual precipitation at the recording rain gage in Middle Fork was (with standard error) 32.8 ± 1.5 inches from 1938 through 1981. Approximately two-thirds of the precipitation falls during the October to May winter period, usually as snow. Numerous, intense thunderstorms occur in a rainy season from July through September.

Perennial streamflow was recorded continuously at 90° V-notch weirs on North Fork and on South Fork and at a combination 90° V-notch and 7-foot Cipoletti weir at Main Dam on the main watershed below the confluence of the three watersheds. Control watershed (Middle Fork) streamflow was not gaged separately, but is calculated by substracting the South and North Fork values from the Main Dam streamflow (Rich and Gottfried 1976). Average annual runoff for the entire watershed at Main Dam prior to treatment in 1953, was 3.30 ± 0.69 inches. Mean runoff values for all three sub-watersheds were within 3% of the average for Main Dam.

Mixed-conifer stands of Douglas-fir *(Pseudotsuga menziesii)*, white fir *(Abies concolor)*, and ponderosa pine *(Pinus ponderosa)* originally occupied the more moist site, while almost pure ponderosa pine stands were found on drier sites. New Mexico locust *(Robinia neomexicana)* and Gambel oak *(Quercus gambelii)* were common understory trees. Average basal area was about 189 ft² per acre for all trees 1 inch d.b.h. and larger.

WORKMAN CREEK TREATMENTS

The Workman Creek watersheds were established in 1939 to determine the hydrology of mixed conifer forests and

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changes in streamflow and sedimentation caused by land management treatments. The objective on North Fork was to determine the potential for water yield improvement by removing the vegetation in a series of steps, and converting to a grass cover. The South Fork objective was to evaluate changes resulting from forest management activities. The sequence of treatments is presented in table 1. The treatments and their effects on annual and seasonal water yields are summarized below from Rich and Gottfried (1976).

South Fork

The first treatment in 1953 was a single-tree selection harvest, which, with roads, skid trails, and stand improvement work, reduced watershed basal area by 36%. In July 1957, a 60-acre wildfire in the upper end of South Fork destroyed another 9% of the original basal area. The harvest and burn (1954-66) resulted in a statistically significant water yield increase of 0.24 ± 0.20 inch (7 ± 6%); however, the increase was so small that it was considered insignificant from a practical point of view. No detectable water yield changes occurred after the 1957 wildfire, but Rich (1962) reported that all flood peaks for the first two summers were higher than expected; the largest storm peaked to 157 csm, twice the value of the previous high event.

A commercial harvest in 1966 removed most merchantable trees and thinned the remainder in an effort to convert the mixed conifer stand to ponderosa pine with a proposed final stand density of 40 ft²/acre, considered optimum for combined timber and water production. Unstocked areas were planted with ponderosa pine seedlings. This treatment, which affected 83% of watershed, resulted in an average annual water yield increase of 4.20 ± 1.08 inches (110 ± 29%) from 1967 through 1979.

North Fork

The first treatment in August 1953 was a riparian cut of broadleaved trees consisting of Arizona alder *(Alnus oblongifolia)* and big tooth maple *(Acer grandidentatum)* along streams, springs, and seeps. This treatment, which removed 0.6% of watershed basal area, did not produce a detectable increase in seasonal or annual runoff.

Nearly one-third (80 acres) of the watershed adjacent to the channel was cleared of its moist site forest of predominantly Douglas-fir and white fir by a timber harvest in 1958. The cleared area was seeded to grass. The moist site treatment (1959-66) increased water yields by 1.28 ± 0.28 inches (42 ± 10%), most of the increases occurring during the 8-month winter period.

The final North Fork treatment in 1966 converted 100 acres (40%) of dry-site merchantable ponderosa pine, upslope from the moist-site area, to grassland. Grasses were seeded, and New Mexico locust invaded the cleared sites, as occurred on the moist-site clearing. Streamflows from 1967 through 1979 increased 1.77 ± 2.99 inches (37 ± 45%) above those produced by the moist-site treatment. The combined moist- and dry-site treatments (1959-79) increased streamflow by 2.65 ± 0.80 inches (72 ± 22%).

DATA ANALYSIS

The hydrographs from 40 years of records (1940-1979) were reviewed for rain-generated-stormflow events 0.001 inch and larger, which occurred simultaneously on all three watersheds. Stormflow hydrographs were partitioned into stormflow and delayed flow components using the hydro-

Table 1.--Schedule of treatments for the Workman Creek watersheds.

Water years	Treatments				
	North Fork	No. of years	Middle Fork	South Fork	No. of years
1939-53	Calibration	15	Calibration	Calibration	15
1954-58	Riparian cut of broadleaf species	5	Control		
1954-56				Start of single-tree selection harvest	3
1957-58				Wildfire	2
1959-66	Convert moist site to grassland	8	Control	Interim period	8
1967-79	Convert dry site to grassland	13	Control	Commercial clearcut to convert to a pure ponderosa pine stand with a basal area of 40 ft./acre	13

graph separation technique developed by Hewlett and Hibbert (1967). Separation was arbitrarily determined by projecting a line of 0.05 csm/hr slope from the storm hydrograph rise to the recession limb. Peak flow rate is maximum hydrograph peak minus initial flow rate at rise of storm hydrograph.

The data were analyzed by winter (October-May) and summer (June-September) periods. Different techniques were used to evaluate the two periods. Changes in summer stormflows and peaks were determined by comparing the relationship between stormflow volume or peak and storm rainfall. Increases were calculated by comparing the regression coefficients of the pre- and posttreatment relationships. Exponential regression relationships were developed for each treatment period using log-transformed data to control variance. Regressions of the transformed data were significant ($P \leq .05$), with the r^2 values ranging from 0.27 to 0.54. The pre- and posttreatment regressions were compared in a covariance analysis using dummy values to separate treatment periods.

Winter events could not be analyzed by the runoff-precipitation relationship because of the variability caused by rain on snow, where the actual daily inputs of snowmelt into the channels were unknown. Winter stormflow volumes were analyzed by comparing before- and after-treatment linear regressions developed from paired events on treated and control watersheds. Regressions had r^2 values between 0.82 and 0.93. Two sets of regressions were developed: one for stormflow volumes up to 2.5 inches (2 large snowmelt-dominated stormflows between 4 and 8 inches were rejected as outliers), and the other for smaller stormflows of less than 0.5 inch. Posttreatment regressions were compared with the respective pretreatment regression, and a combined regression was then developed to describe the differences between the two relationships. Covariance analysis was used to compare the slope and intercept coefficients of the pre- and posttreatment regressions. The differential slope and intercept coefficients of the combined regression reflect this comparison. Differences in the slope coefficient indicate that a treatment has a multiplicative effect, where the dependent variable increases more rapidly than does the independent variable.

No analysis was made on winter peaks. The arrangement of weirs on Workman Creek, and the need to calculate Middle Fork (control watershed) values, makes it difficult to separate peak flows on Middle Fork from the peaks on the other two watersheds.

RESULTS

Summer Storms

Summer stormflows and peaks increased after each treatment compared with pretreatment levels, when storm rainfall is used as the independent variable in a log-transformed regression analysis (table 2). The increases were exponentially related to storm size (fig. 1) for storm rainfalls between 0.5 and 2.5 inches. Small storms of less than 0.5 inch were excluded from the analysis because of the large variability attributed to the spotty nature of storm coverage on the watersheds. Peak flow response curves are not shown, but were very similar to the stormflow curves in figure 1.

South Fork

The largest increases in summer stormflows and peaks over pretreatment conditions occurred on South Fork during the two summers after the 60-acre burn. Stormflow volumes increased from 2.5 to 3 times, and peaks increased from 5 to

Table 2.--Changes in summer stormflows and peaks after various treatments on Workman Creek watersheds.

Treatment	N	Stormflows				Peaks			
		At Ppt = 1 in.		At Ppt = 2 in.		At Ppt = 1 in.		At Ppt = 2 in.	
		Inches	%	*Inches*	%	*csm*	%	*csm*	%
South Fork									
Pretreatment	54	0.0023[1]	--	0.0079[1]	--	1.47[1]	--	3.97[1]	--
Single tree	26	0.0018	78	0.0177	223	0.7	49	4.0	102
60-acre burn	12	0.0062	264	0.0450	564	3.8	264	33.8	848
Postburn interim	52	-0.0003	-12	0.0039	49	-0.3	-22	0.4	10
Commercial	69	0.0021	90	0.0103	130	0.8	54	3.6	91
North Fork									
Pretreatment	54	0.0008[1]	--	0.0033[1]	--	0.51[1]	--	1.54[1]	--
Riparian	37	0.0007	92	0.0093	280	0.3	51	2.3	149
Moist site	52	0.0026	322	0.0150	442	1.6	304	6.4	411
Dry Site	69	0.0030	378	0.0125	378	1.5	299	4.8	307

[1]These are pretreatment means which are the basis for computing percent changes after treatment.

10 times above values recorded during the previous three years following the single-tree selection harvest. The harvest, however, also showed a substantial percentage increase of 223% over pretreatment level for 2 inches of rain (table 2, fig. 1), although the increase was only 0.018 inch of flow volume. After the first two postfire summers, stormflows and peaks returned to near pretreatment levels, and became nonsignificant for the next eight summers of the interim period (1959-66). Stormflows and peaks during the commercial harvest period (1967-1979) were less responsive to summer storms than during either the selection harvest or wildfire. An exception was for storms of less than 1.5 inches of rainfall, when the response was essentially the same as for single-tree selection harvest (fig. 1).

North Fork

The riparian cut increased summer stormflows and peaks during the 5-year posttreatment period by up to 280% (0.009 inch) at 2 inches of rainfall, even though no annual or seasonal runoff increases were detected for this treatment by previous investigators (Rich and Gottfried 1976). The moist-site cut, on 32% of the watershed next to the channel, increased summer stormflows and peaks from 322% to 442% (0.003 to 0.015 inch) over pretreatment levels for rains of 1 to 2 inches, or roughly twice as much as was caused by the riparian cut. After the dry-site cut on the upper slopes of North Fork, increases in stormflows and peaks dropped back slightly for storms greater than 1.5 inches, although they were still four or more times larger than expected without treatment (table 2, fig. 1).

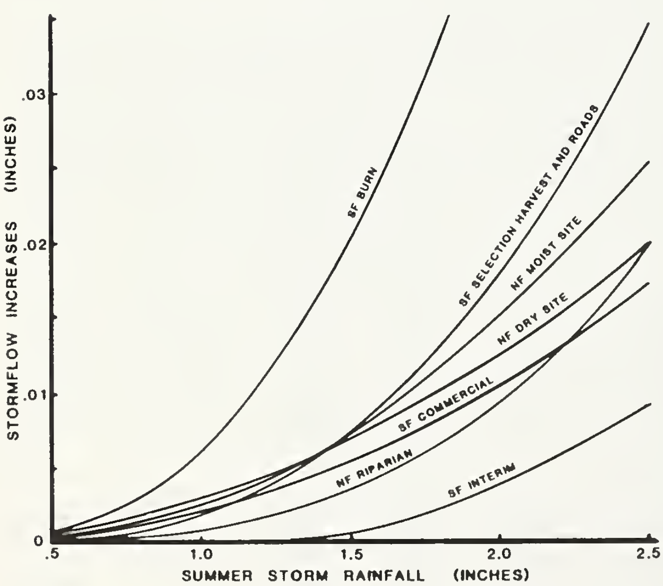

Figure 1.--Summer treatment response curves developed from differences between posttreatment and pretreatment stormflow regressions on storm rainfall.

Winter Storms

Winter stormflows responded less to treatment in terms of percent increase than did summer stormflows, although the actual flow volume increases were larger. Linear regressions using all data except 2 outliers indicated statistically significant increases in the differential slope coefficients for each treatment period (rows 1, 2, 5, 6 in table 3). Additional regressions were run on small storms only by limiting the range of control watershed stormflows to less than 0.5 inch (rows 3, 4, 7, 8 in table 3). The reason for classifying the data in this way was to examine the possibility of the increases being larger for small storms than for large storms, a trend indicated by a regression analysis of log transformed data.

The results were mixed: the largest increases in regression slope change for North Fork treatments were in the ≤0.5-inch stormflow range (rows 7 and 8, table 3). For the South Fork, a small nonsignificant decrease was indicated for the combined selection cut, burn, and interim period (row 3, table 3), and a marginally significant (P= 0.06) increase was shown for the commercial cut (row 4, table 3). The results are heavily influenced by small events because 75 to 87% of the stormflows were smaller than 0.5 inch. The lack of stormflow response in the first treatment period on South Fork (row 3, table 3) is consistent with earlier evaluations, which showed very little annual or seasonal increase from these treatments (Rich and Gottfried 1976). However, this lack of small stormflow response for the first treatment period on South Fork changes to a strong response when seven larger storms (0.5-2.5 inches) are added to the analysis (row 1, table 3). It is possible that, after treatment, South Fork was more responsive to larger storms than was North Fork. Predictions based on the 0-2.5 inches data set must be made with caution because of the disproportionate influence of the small number of storm events larger than 0.5 inch.

Winter stormflow volume increases (last columns in table 3) were calculated by taking the difference between posttreatment and pretreatment regressions evaluated at control watershed stormflow levels of 0.5 inch for the ≤0.5 inch data set, and 2 inches for the larger stormflow range. It is apparent that, while the percent increases are much less than for summer storms, the actual increases in stormflow volumes are much larger.

SUMMARY AND CONCLUSIONS

The changes in summer stormflows and peaks, which increased exponentially with storm rainfall after various treatments, indicate the sensitivity of the channels and channel-side environments to vegetation removal and soil disturbance. These increases in stormflows and peaks are largely attributed to decreased interception of rainfall caused by removal of the vegetation along the channels, and to more direct runoff into the channels from roads, skid trails, and from other disturbance, such as the wildfire.

Table 3.--Increases in winter stormflows after treatments on Workman Creek Watersheds.

Row	Treatment period	Number of paired events	Range in control watershed stormflow	Linear Regression Coefficients: Differential intercept			Differential slope			Calculated increase[1]	
			Inches	Inches	%	P value	Slope	%	P value	Inches	%
	South Fork										
1	Selection cut, burn, interim	44	0.0-2.5	-0.28	-86	ns	0.303	69	0.0001	0.58	63
2	Commercial	44	0.0-2.5	-.005	16	ns	.423	96	.001	.85	92
3	Selection cut, burn, Interim	37	0.0-0.5	.002	75	ns	-.118	-13	ns	0	0
4	Commercial	39	0.0-0.5	.012	382	ns	.186	20	.06	.11	22
	North Fork										
5	Moist site	25	0.0-2.5	-.005	-17	ns	.262	32	.0001	.52	31
6	Dry site	44	0.0-2.5	.032	119	ns	.121	15	.02	.27	16
7	Moist site	20	0.0-0.5	.002	37	ns	.400	33	.02	.20	33
8	Dry site	39	0.0-0.5	.022	548	ns	.310	26	.02	.18	29

[1] Increases in winter stormflow were calculated at 0.5 inch of control flow using the regressions for the 0-0.5 inch data range, and at 2.0 inches using the regression for the 0-2.5 inches data range.

However dramatic the percentage changes appear to be, they are modest in terms of actual flow volumes and peak rates. The greatest changes were produced by the wildfire on South Fork, where an increase of 564% was equivalent to a 0.045-inch runoff from a 2-inch storm, or about 2% of the rainfall. The 858% change in peak flow was equivalent to an increase of 34 csm. However, except for very localized impacts on the watershed and in the channel, the actual increases were too small to be of significance from a land management standpoint. Even the wildfire related increases were readily absorbed in the channel system within a mile or so downstream, although a larger burned area would have had a greater impact downstream.

Winter stormflow increases were readily detectable only for treatments that affected vegetation on one-third or more of the watershed. The increases are primarily attributed to lower growing-season evapotranspiration, which results in quicker soil recharge and more efficient moisture movement. Summer storms contributed little to streamflow other than rain falling directly onto the channel surfaces and streamside areas. Therefore, the potential for downstream flow rates to be materially affected by treatment is greater in winter than in summer. This is anticipated, since most of the water yield increases detected in the annual streamflow analyses, up to 110% on South Fork, must be accounted for in the wet season flows. However, we looked at less than one-third of the total streamflow in our analyses because snowmelt, which dominates the runoff process at Workman Creek, was not included. Water yield studies in Colorado have suggested that the effects of forest treatments on snow accumulation and on snowmelt account for a major part of the increased runoff (Troendle 1983).

There is evidence from studies in Oregon and California, for example, Ziemer (1981), that large stormflows are not greatly affected by forest treatments. We were unable to verify similar trends at Workman Creek because of the small number of large storms, although observation during a few large rain on snow events suggest little or no difference between treated and untreated responses from the three catchments. Therefore, we generally agree with the concept that upstream treatment effects tend to become negligible once the soil mantle is fully charged. At that point, the amount of precipitation or snowmelt entering the system determines streamflow volumes.

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2H5

The Influence of Pinyon-Juniper on Microtopography and Sediment Delivery of an Arizona Watershed

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Abstract--Hummocks formed by litter fall of pinyon-juniper trees resulted in soil formation. Overland flows were diverted and slope gradients decreased by about 57%. In turn, streampower decreased. It is proposed that this was responsible for the decreased sediment delivery. Where buffer strips exist below non-wooded areas, sediment delivery was practically nullified.

In the Southwest, woodlands cover an area of about 25 million hectares. Pinyon-juniper represents an important vegetation type on this land, and occupies more than seven times the area of chaparral in Arizona. The use of this large area is limited to cattle grazing, fuelwood cutting, and occasional recreation. More intense use of the resource, such as charcoal production, started in places but failed on economic grounds. Vegetation type conversions to grass were unsuccessful because of increased erosion and insufficient water yield increases (Gifford et al. 1970, Gifford 1975, Roundy 1976). Unauthorized tree cutting is problematic in woodlands near rural communities, largely because of insufficient manpower available to management.

With the exception of silvicultural and fire research, pinyon-juniper has received little scientific attention. Thus very little is known about the erosional processes operating in this vegetation type, and the interactions between vegetation and erosion processes.

Pinyon-juniper usually occurs in open stands with wide spacings between individual trees. Some stands form large clusters. The question therefore arises: can mosaic distributions of pinyon-juniper significantly influence overland flow and sediment transport? The primary objectives of our ongoing study are therefore to quantify overland flow and sediment delivery, and to determine their production is influenced by pinyon-juniper.

Study Area

Located at an average elevation of 2,300 m in the Arizona White Mountains, the study watershed represents the typical present-day condition of the pinyon-juniper zone in the Southwest: overgrazed by cattle during the turn of the century, followed by controlled grazing and fuelwood harvest. During our study, fuelwood cutting was not permitted on the watershed. The climate is semi-arid with 395 mm average annual precipitation, of which 66% falls in summer. Summer storms are of high intensity. From November to April, precipitation is mainly in the form of snow. The soils of the area are sandy clay loams, with basalts forming the geologic base.

Method

Thus far, only two years of data are available. Twelve microwatersheds, or hillslope segments, were selected to represent three different woodland cover types: (1) four wooded, (2) six non-wooded, and (3) two non-wooded with buffer strips on the downslope border. Wooded cover formed a mosaic pattern comprised of open areas and trees and tree clusters. In this type, erosion pavements averaged 40% of the area. The pavements were a matrix of different rock sizes covering the ground surface. Ground cover of the non-wooded or open areas consisted of erosion pavement in nearly all cases.

Pinyon-juniper buffer strips consisted of 5- to 8-m-wide strips of trees close to the topographic contour. Open areas upslope from the strips had bare ground and erosion pavement. The trees in the strips were spaced so closely that erosion pavements did not exist between them, and the ground was fully covered by needle fall. Of the total area, erosion pavement averaged at 60%.

These small microwatersheds were neither subwatersheds nor plots. Generally, subwatersheds are larger in size. In contrast to plots, gentle topographic swales represented the

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microwatersheds where available. When not available, the miniature watersheds were hillslope segments bounded by 20-cm-wide sheet metal strips sunk about 10 cm into the ground. These strips were also placed where the natural overland flow divides were not sufficiently pronounced to prevent breaching during strong runoff events.

At the downhill drainage boundary, 4-m-long prefabricated metal troughs were installed. These conveyed the water-sediment mixture into tanks, where overland flow volumes and sediment concentrations were measured after each storm. Where expected flow volumes were too large for the tanks, home-made splitters (consisting of a steel blade installed plumb into a 10-cm pipe) wasted 50% of the flow volume and conveyed the remainder to the tank.

At least one continuously recording flow gaging station was placed in each cover type drainage. Small supercritical flumes with waterstage recorder or bubble flow meter and pumping sediment samples were used. The bubble flow meter and sediment sampler were synchronized so that flow hydrographs delivered by the meter could be correlated with sediment yields.

Since microwatersheds occupied different aspects and elevations on the mountain slopes, a precipitation gage network was installed so that individual estimates for each drainage were obtained.

No unusual precipitation or flow events occurred during the study period. To determine whether precipitation during the study years was normal, 14 years of data from a station, 5 mi from the study site, were compared. A linear regression between the precipitation of the nearby-station and the study area showed a coefficient of determination (r^2) of 0.71. Based on this regression, our precipitation data were calculated back to 1972. The estimated mean precipitation (453 mm) did not differ significantly from the actual mean 423 mm) ($p = 0.5$), indicating that precipitation was normal during the study period.

Statistical analyses consisted of analysis of variance and Student's t-test.

Results and Discussion

Sediment deliveries from the three vegetation cover types varied greatly (table 1). Wooded areas produced an annual average of 165 kg ha^{-1} yr^{-1}, non-wooded 556 kg ha^{-1} yr^{-1}, and non-wooded with buffer strip 31 kg ha^{-1} yr^{-1}. However, when overland flows were compared between wooded and non-wooded conditions, no significant difference ($p = .05$) could be found. This contrasts with the sediment deliveries that were significantly different ($p < .01$). Student's t-test was applied.

The apparent contradiction between similar flows but dissimilar sediments was puzzling. Both types had erosion pavements. Earlier studies have shown that erosion pavements are high sediment producers on a watershed[2,3] (Heede 1984).

At times, annual herbaceous vegetation invaded the erosion pavement, but never represented more than 2-3% of the cover. In contrast to the wooded area, erosion pavement formed a continuous ground surface cover on the non-wooded study sites. No apparent relationship was observed between slope gradient and sediment delivery. For instance, on wooded slopes, 175 kg ha^{-1} yr^{-1} were delivered from a 17% gradient and 172 kg ha^{-1} yr^{-1} from a 34% gradient (table 1). This implies that slope gradient was not the main influencing variable.

Inspection of the microtopography of the hillsides showed that each tree and tree cluster had formed a mound protruding up to 0.36 m above the surrounding ground surface. Average mound height was 0.20 m with a standard deviation of 0.08 m. The outline of this mound coincided with the dripline of the tree. Viewed from some distance, the mound formations transformed the hillsides into a landscape of miniature hummocks. Individual hummocks were formed by deposition of dead needles. Hummock height tended to increase with age of tree. In contrast with erosion pavements surrounding the hummocks, soil had developed beneath the litter and duff layers. Where trees had died or were removed, the hummocks began to shrink in size and finally disappeared. As this happened, the soils of the hummocks also disappeared, and erosion pavements replaced the hummocks underneath the tree "skeletons."

Overall, hummocks appeared to be effective barriers for overland flow, and only seldom was one overrun (indicated by rill formation). In nearly all cases, diversion of the overland flow was diverted around the hummock, as evidenced from the flow pattern after storm events. This diversion produced considerable lengthening of the flow lines compared with more or less straight downhill flows. If we consider the ideal case of a hummock with a true circular circumference, the increase in flow length necessary to reach the same elevation as existing at the tree (center of circle) is 57% (because the length of the flow line r, the radius of the hummock, is increased to $1/2\ r\ \Pi$, one fourth of the circle's perimeter). From this follows a decrease of the flow gradient by 57%. Of course, we are not dealing with a tilted tabletop and regular geometric form; this decrease could therefore be somewhat larger or smaller. But the point is that a substantial gradient decrease takes place which, in turn, leads to decrease of the velocity of flow.

Slope and velocity are two important variables for streampower, an expression for sediment carrying capacity of the flow. Bagnold (1973, 1977) described stream power (ω) by the equation

[2]Heede, Burchard H. The influence of vegetation and its distribution on sediment delivery from selected Arizona forests and woodlands. In preparation for Proceedings of Nineteenth Annual Conference of the International Erosion Control Association. 1988.

[3]Heede, Burchard H. Overland flow and sediment delivery five years after timber harvest in a mixed conifer forest, Arizona, U.S.A. Journal of Hydrology (In press).

Table 1.--Average annual overland flow and average annual sediment delivery from the three different vegetation cover types. Standard deviations given in parenthesis.[1]

Microwatershed No.	Aver. slope gradient	Overland flow	Sediment delivery
	$m\ m^{-1}$	$mm\ yr^{-1}$	$kg\ ha^{-1}\ yr^{-1}$
Wooded			
3	0.17	3.8	174.83
5	.34	1.6	195.39
12	.34	3.6	172.42
13	.28	.7	117.87
Average	.28 (0.20)	2.4 (1.5)a	165.13 (28.71)a
Non-wooded			
4	.33	4.0	291.73
6	.35	3.1	828.46
7	.34	2.7	353.38
9	.41	4.5	623.85
10	.10	2.0	405.71
11	.12	7.8	835.69
Average	.28 (.12)	4.0 (2.0)a	556.47 (220.05)b
Non-wooded with bufferstrip			
1	.29	.9	46.94
15	.20	.7	15.45
Average	.25 (.06)	.8 (0.2)b	31.20 (22.88)c

[1]Within a column, significant differences between classes are indicated by different letters (flow, $p = .05$, sediment, $p < .01$).

$$\omega = \gamma\, dSv \qquad [1]$$

where q is the absolute density mass per volume, d is the mean flow depth, S is the energy slope, usually substituted by bed slope, and v the mean flow velocity. As can be seen from this equation, the computation of absolute changes in stream power induced by overland flow diversions would be theoretical, since mean flow depth, mean velocity, and their changes would have to be estimated, while γ could be taken as constant. Measurements of the variables under field conditions possibly would lead to closer estimates, but not to absolute values, due to the difficulties of measurements in shallow flows and rapidly changing depths and velocities. It can be reasonably assumed that slope gradient and velocity will substantially decrease, exceeding any possible increase in flow depth due to lack of channelization. In turn, this leads to wider flows, increased wetted perimeter and roughness of flow, and decreased velocities.

Figure 1.--Buffer strips consisted of a cluster of trees that had formed on continuous mound underneath their crowns. The overland flow and sediment collector trough is located at the bottom of the figure (looking upslope).

Thus, streampower would decrease with overland flow diversions induced by hummocks. Generally, diversions occur several times as water flows downslope, resulting in flow regimen changes from a turbulent to a more tranquil flow, and further decreased sediment carrying capacity.

It is proposed, but has not been tested, that the significant difference in sediment delivery between the pinyon-juniper mosaic pattern and the open area is caused by the hummock formations. The apparent contradiction that hummocks led to decreases in sediment delivery, but slope gradient-sediment delivery relationships did not exist on the microwatersheds, can be explained by the cumulative effect of several hummock diversions.

Unfortunately, only two sites of non-wooded areas with buffer strip had a complete data set (table 1). If we assume that average sediment production on the erosion pavement upslope from the buffer strips was similar to that from the non-wooded sites, only an average of about 6% of sediment left the buffer strip. In ponderosa pine (Heede 1984) and in chaparral (Heede, in preparation[2]), only 2% and 0.4%, respectively, left the buffer strips. The face value of the data is not as important, as what they reveal about processes.

The data indicate that pinyon-juniper buffer strips were more effective in reducing sediment delivery than the wooded sites, because the upslope microtopography forced the overland flow to enter the extended hummock of the strips' tree clusters. Therefore, due to increased infiltration, the litter-soil ground cover underneath the trees reduced the flow and with this the sediment load.

Conclusions

Sediment delivery from wooded areas was lower than from non-wooded sites, but overland flow was not. Pinyon and juniper trees changed the microtopography by forming mounds, or hummocks, whose edges corresponded to the tree's dripline. Litter, duff, and soil making up these hummocks protruded up to 0.36 m above the surrounding ground surface. I observed that the elevational difference forced overland flow to circumvent the trees. This caused extension of the flow lines and reduction of the slope gradient by about 57%. If the flow line extension is the predominant variable responsible for the decrease of sediment delivery, resulting decrease of sediment carrying capacity of the flow would explain the reduced sediment delivery from wooded sites.

Sediment delivery from pinyon-juniper buffer strips was practically nil. Similar results had been obtained by the author below buffer strips in ponderosa pine and chaparral.

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Environmental Limitations to Photosynthesis in Subalpine Plants of the Central Rocky Mountains, USA

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Abstract--In the subalpine forests of the central Rocky Mountains, the specific environmental factors which limit photosynthetic carbon gain of the conifer tree species during the summer growth period are not well understood. Suboptimal air and soil temperatures, soil and air dryness, and cloudcover have been identified as potentially important factors which interact to limit summer carbon gain. Recently, our studies using field gas exchange measurements of photosynthetic carbon assimilation in the dominant tree species indicate that prolonged, near-freezing air temperatures and cool soil temperatures (< 8°C) exert a strong inhibition during early summer. Soil drying appears to have potentially strong influences only at lower elevations while the stomatal response to air dryness is secondary during most of summer.

The summer growth period in the subalpine region of the central Rocky Mountains is characterized by extremely variable environmental conditions that are enhanced by the structure of the lodgepole pine and spruce-fir forests. The openness of these forests enable substantial sunlight penetration and, yet, wind speeds may be severely reduced (Smith 1985). These environmental characteristics result in a host of relatively unique stresses that are apparent in the ecophysiology of the endemic conifers. For example, air temperatures may approach freezing at night during any summer month and, yet, rise to 20°C during the day. Soil temperatures may not exceed 10°C at 10 cm depths within the forest where considerable shade and snow accumulation can result in prolonged snow cover. Yet, low ambient humidities (< 20% rh) and high vapor pressure deficits (> 5 kPa) appear common and the biophysics of high elevation generates an especially strong evaporative demand on plant tissues (Smith and Geller 1980). Table 1 and figure 1 summarize some of the hypothetical, temporal aspects of the above environmental parameters which are potential limitations to photosynthetic carbon gain during the summer growth period.

While understory saplings experience considerable portions of day in shade, even adult overstory trees also experience regular and substantial summer cloudcover due to daily advectional cloud formation particularly in the afternoon. A major portion of a typical summer day throughout the entire summer may be cloudy with substantial periods of reduced sunlight levels that are well below photosynthetic saturation (Knapp and Smith 1987, Young and Smith 1983). Virtually no information exists regarding the importance of cloudcover regimes to seasonal carbon gain in subalpine species.

Over the past several years we have attempted to identify and quantify the specific environmental limitations to carbon assimilation imposed at a particular time of summer by a single environmental factor. We realize that at any given time an interactive effect of many environmental variables is most likely occurring. However, by attempting to quantify individual influences, identification of the most important factors will be possible and will subsequently enable an evaluation of the specific structural/physiological capabilities in a species that might be most adaptive. Our ultimate goal is to be able to evaluate the importance of physiological adaptations to natural distributional and successional processes as well as to the reestablishment and regeneration problems important for successful subalpine forest management.

Our initial approach was to focus on leaf conductance (stomatal behavior) patterns in subalpine conifers as an overall indicator of the potential for carbon assimilation and growth. We have recently begun to utilize photosynthetic measurements which enables quantification of both stomatal (leaf conductance of CO_2) and non-stomatal (cellular, enzymatic processing of light and CO_2) limitations to photosyn-

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Table 1.--Hypothetical interaction between plant and environmental water parameters within the sprucefir zone during the growth season. Double asterisks indicate a primary limiting effect, either directly on stomatal opening (stomatal) or indirectly through limitations on water uptake from soil and/or movement to the leaves (recharge). Single asterisks denote important, but less significant effects. Based on the interactive model proposed by Smith et al. (1984).

	Late spring		Early summer		Midsummer		Late summer		Fall	
	stomatal	recharge	stomatal	recharge	stomatal	recharge	stomatal	recharge	stomatal	recharge
Air temperature	**	*		*					**	*
Soil temperature at root depths		*		**		*				*
Morning xylem pressure potential	*		*				*			
Afternoon xylem pressure potential					*		**			
Soil water potential at root depths								**	*	
Leaf-air water vapor deficit			*			*	*			

thetic carbon assimilation (Jones 1985). Although stomatal function is especially appropriate for water relations studies, photosynthetic limitations due to non- stomatal influences are often of equal if not greater importance (Farquhar and von Caemmerer 1982).

Methods and Materials

All measurement sites were located in the Medicine Bow Mountains of southeastern Wyoming. The dominant conifers include lodgepole pine (*Pinus contorta* Dougl. ex Loud. ssp. *latifolia* (Engelm.)), subalpine fir (*Abies lasiocarpa* Nutt.), and Engelmann spruce (*Picea engelmannii* Parry). Data presented in the following sections are based primarily of field gas exchange instrumentation utilizing cuvettes that enclose branch tips, including primary and/or secondary shoots. Smith

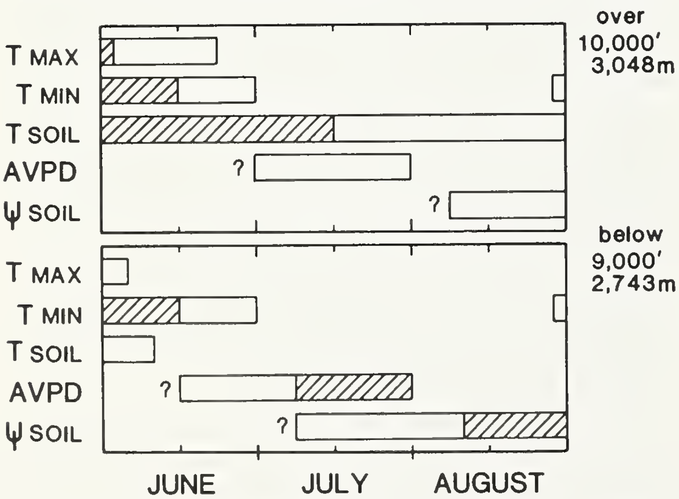

Figure 1.--A hierarchial model of environmental limitations to photosynthesis in Engelmann spruce. The hatched bars indicate a strong limitation (> 20%) and the open bars indicate a slight limitation (5 to 10%) to photosynthesis at high (≥ 10,000 feet, 3048 m) and low (≤ 9,000 feet 2743 m) elevations.

and Hollinger (1987) provide a recent and detailed review of this approach. Also, the references provided in the following sections include detailed descriptions of the specific methods and materials corresponding to an indicated data set.

Results and Discussion

Although numerous studies have dealt with the influence of specific environmental factors on photosynthetic performance, (see Jarvis 1980, Schulze and Hall 1982 for reviews) only a few have attempted a comprehensive evaluation of the relative importance of different environmental constraints at different times of the growth period to seasonal carbon gain. Many of these latter studies have focused on stomatal conductance patterns without photosynthetic measurements (Kaufmann 1982a,b; Smith et al. 1984, Smith 1985a). Stomatal behavior patterns appear to be strongly influenced by photosynthetic photon flux density (PPFD), plant water status (xylem pressure potential, XPP), the leaf-to-air vapor deficit (LAVD), and leaf temperature (fig. 2). In addition, nonstomatal limitations may also involve PPFD and water status, as well as other factors such as carbohydrate feedback inhibition and hormonal effects that have direct consequences on the cellular processing of light energy and the carboxylation process (Delucia 1986).

Air and Soil Temperature

It has been proposed that the temporal sequence of which specific environmental parameter is most limiting to photosynthesis may proceed as depicted in figure 3 (Smith 1985b). Initially in early summer, the continuing (although sporadic) occurrence of near-freezing nights causes a major reduction in stomatal opening and photosynthesis on subsequent days (Delucia 1987, Fahey 1979, Neilson et al. 1972, Pharis et al.

1970, Smith et al. 1984, Smith 1985a). Cold air drainage may extend low nighttime needle temperatures to lower elevations (Kaufmann 1984a). Figure 4 shows the fairly dramatic increase in leaf conductance and net photosynthesis for four subalpine conifers immediately following the onset of above-freezing nights in June. Prior to this disappearance of below-freezing nights, it appears that the capacity for net photosynthesis is approximately half of the maximum rates measured during summer (Delucia and Smith 1987) while leaf conductance may also be severely depressed to even lower values relative to maximum seasonal levels (Smith 1985b). Similar reductions in leaf conductance has been reported for six subalpine conifers after the onset of freezing nights in fall (Smith et al. 1984).

In contrast, low daytime air temperatures appear to have a minimal impact compared to nighttime minimums, at least for clear days. Considerable warming of conifer needles above air temperature under full-sun conditions results in temperatures that are within a relatively broad and high temperature range for maximum photosynthesis (Delucia and Smith 1987, Smith and Carter 1987). Optimal temperatures for photosynthesis, that were considerably higher than maximum daily air temperatures, were attributed to a relatively dense needle packing in conifers (Smith and Carter 1987). As a result, a relatively high percentage of the daytime may be spent within the optimal photosynthetic temperature range (table 2).

Soil temperatures may remain considerably below about 10°C during much of the summer growth period within the subalpine forest (fig. 5). Moreover, seasonal increases in leaf conductance and net photosynthesis appeared correlated with increasing soil temperatures throughout June and July. Potted seedlings of Engelmann spruce had similar response patterns in leaf conductance and net photosynthesis as root temperatures were experimentally increased from near 0°C to 20°C (fig. 6, Delucia 1986). Successive days of exposure to chilling root temperatures caused a dramatic decrease in photosynthesis due primarily to non-stomatal limitations.

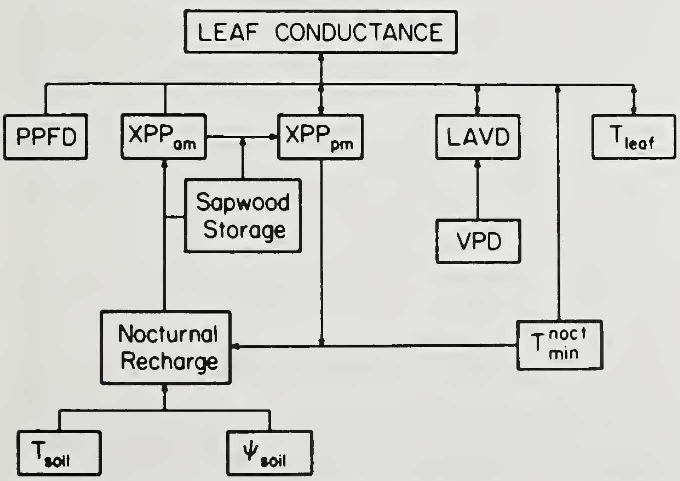

Figure 2.--Interactive relationships between environmental variables, plant water status, and leaf conductance to water vapor diffusion in conifers (Smith et al. 1984).

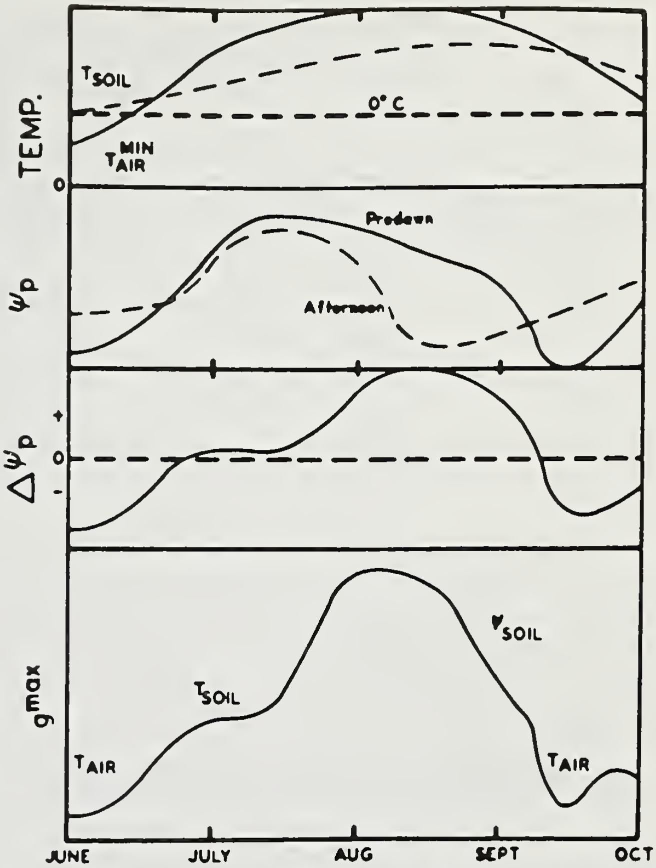

Figure 3.--Idealized relationships between air and soil temperatures, predawn and afternoon minimum, and maximum leaf conductance to water vapor during the day (Smith 1985b).

Because both cold air and soil temperatures may be simultaneously limiting photosynthesis during early summer, it is difficult to segregate independent effects of each. It is apparent that a more prolonged soil temperature inhibition occurs due to the relatively rapid disappearance of freezing nighttime temperatures in June (fig. 2-4). In fact, the laboratory data on the response in photosynthesis to root temperature (fig. 5-6) indicates that cold soil temperatures could be inhibitive for most of the summer at high elevation. Thus, there may be a relatively abrupt increase in photosynthetic capacity in early summer that is followed by a steadily declining inhibition due to cold soil temperatures at root depths.

Water Relations

The ultimate environmental factors influencing photosynthesis via water relations are soil water availability and LAVD. The plants capability for increased rates of water transport, water storage, and/or regulation of stomatal aperature to insure high water use efficiency will dictate the integrative influence of water relations on photosynthetic performance. There appears to be a rather complex seasonal interaction between cold temperature effects and, possibly, soil drying and LAVD (fig. 2). According to rather sporadic measurements in the subalpine forest over the past 8 years (1978-present) summer soil water potentials never fell below about

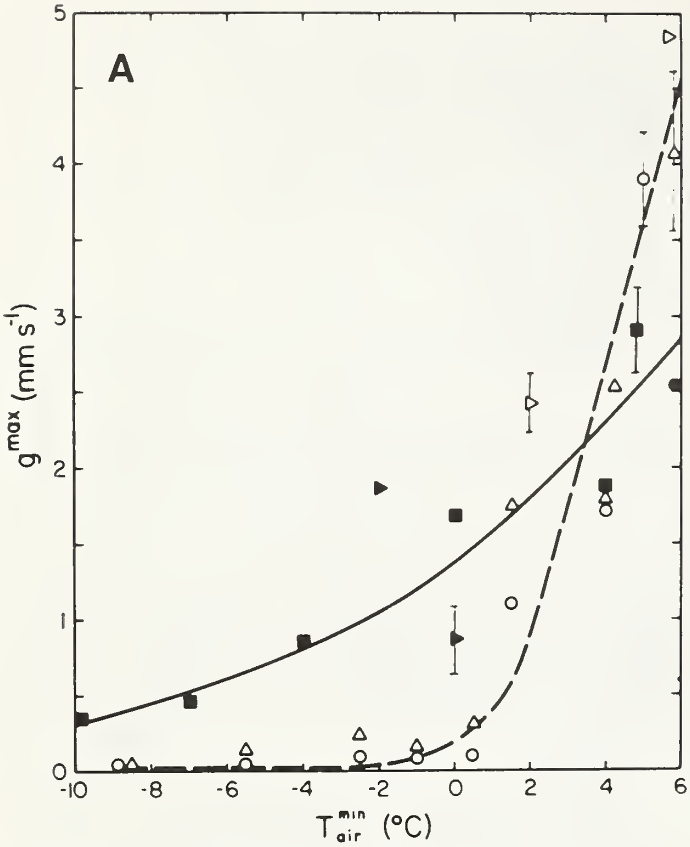

Figure 4A.--Maximum daily leaf conductance (g^{max}) versus the minimum air temperature on preceeding nights in spruce (Δ), fir (0), limber pine ($\triangleright$) and average values for six common conifer species of the Central Rocky Mountains growing naturally at the same location. Solid symbols are for fall (Aug. 26-Sept. 30); open symbols are for early summer (June 5-July 15). Vertical bars represent greatest range of values for each data set (Smith 1985b).

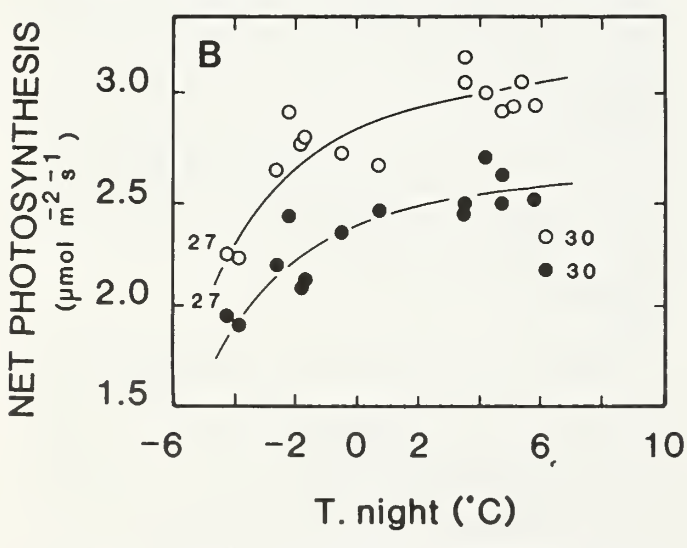

Figure 4B.--The photosynthetic response of Engelmann spruce trees In situ to minimum air temperature for the previous night. Measurements of trees in warm and cool soil are shown with open and closed circles, respectively. Each point is a mean of 5 independent measurements.

1.2 MPa at 10-15 cm depths for a total of over 300 measurement days at 14 different locations (Smith et al., unpublished). Regardless, when subfreezing air temperatures occur at night frozen stems could inhibit nocturnal sapwood water recharge from even wet soils and, thus, lead to lower water status at dawn. Recent data showing greater xylem pressure potentials later in the day compared to predawn values support this idea (Smith et al. 1984, Smith 1985a).

There are numerous reports indicating that stomatal behavior in coniferous trees may respond strongly to LAVD values above about 2 kPa. For subalpine conifers of the central Rocky Mountains LAVD may approach values exceeding 4 kPa due to needle temperatures that are frequently elevated well above air temperature (Smith and Carter 1987) while ambient humidities are usually low (< 20% relative humidity). At these high LAVD values maximum daily leaf conductance never exceeded 0.5 mm s^{-1} over 3 summers of sampling at four different sites (1982-1984). However, the actual frequency of occurrence of these highest LAVD values is quite low with the most frequent values near 1.5-2.0 kPa. The question arises as to how often partial stomatal closure occurs and, if so, how much influence is exerted on photosynthetic capacity. Partial stomatal closure can certainly have nearly proportional effects on transpirational water loss (disregarding needle temperature and LAVD adjustments), but considerably less effect on net photosynthesis if non-stomatal limitations are also present. Considerably more work is needed to clarify the photosynthetic influence of the stomatal response to LAVD under natural conditions.

Photosynthetically Active Radiation

Until recently the influence of variable sunlight has not been systematically evaluated as a limiting factor to photosynthetic carbon assimilation in subalpine conifers. Studies dealing with PPFD effects on subalpine conifer photosynthesis have almost exclusively dealt with successional questions involving understory saplings or seedlings. This is somewhat surprising since subalpine areas are always at relatively high elevation where strong orographic influences tend to create considerable moisture deposition and advective cloud formation. Recent evidence now suggests that cloud periods are common to subalpine areas and can be characterized according to duration, intensity, and frequency of occurrence (Knapp and Smith 1987, Young and Smith 1983).

Numerous, alternating exposures to direct sunlight and full shade may comprise over half of a typical day in the subalpine. Physiological adjustments to sun/shade transitions due to cloud pattern involve both stomata and non-stomatal responses (Knapp and Smith 1987). Considering only the length of time spent in full shade (4-6 hrs./day), the corresponding drop in net photosynthesis would deplete daily carbon gain by almost 50%. In general, full cloud shade intervals result in decreases in PPFD of from above 1800 mol m^{-2} s^{-1} to less than 400 mol m^{-2} s^{-1}, decreasing net photosynthesis to about one-half light-saturated values (light saturation points reported for

Table 2.--Importance of elevated needle temperatures to conifer shoot photosynthesis in P. engelmannii (S), A. lasiocarpa (F), and P. contorta (P) during the summers of 1982-1986. Plus and minus values are 95% confidence intervals (Smith and Carter 1987).

Period	Species	Number of shoots	Temperature range for maximum photosynthesis	Mean maximum daily air temperature (°C)[b]	Maximum photosynthesis (% of day) Actual	T_a	Percent increase in daily CO_2 uptake[a]
June 9-23	S,F,P	2,2,2	13-22,15-24,13-25	13.8 . 2.3	64	32	26
June 1-16	S,F,P	3,3,2	14-24,14-26	15.6 . 1.9	59	30	29
July 16-24	F	2	14-26	16.7 . 1.6	56	29	33
July 1-14	S,F,P	2,2,1	15-27,14-25,13-24	17.4 . 1.8	65	32	35
July 16-28	S,F,P	2,2,2	16-26,15-26	16.9 . 1.6	49	26	20
Aug 17-24	S,F,P	4,4,4	15-26,14-24,16-23	14.6 . 1.9	53	31	29
Mean			14.1-25.1	15.8 . 1.2	58	30	29

[a]Each value is computed for the indicated number of fir sun shoots only.

[b]12-year means (1962-1974, Wyoming Solar Observatory, see text).

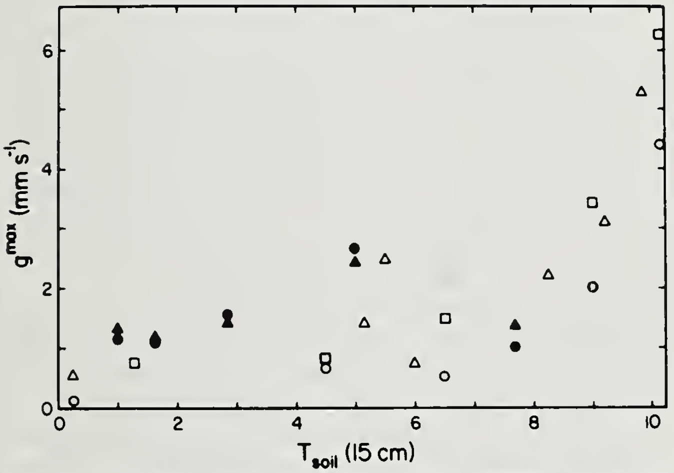

Figure 5A.--Maximum daily leaf conductance (g^{max}) and soil temperatures at 15 cm measured between 0600 and 0800 hr during the summers of 1982-84 (Smith 1985b).

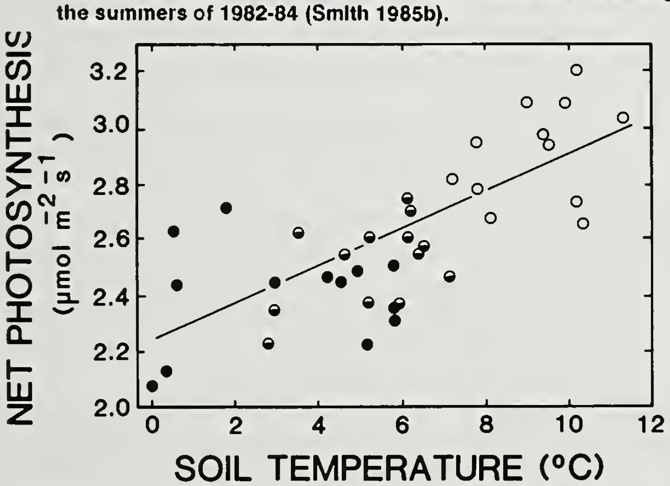

Figure 5B.--The photosynthetic response of Engelmann spruce trees in situ to soil temperature (15 cm) at the time of measurement. Each point is the mean of 5 independent measurements. Snow-free soil, partially covered, and completely snow-covered soil are indicated by open, half closed, and closed circles, respectively. Photosynthesis = 2.26 + 0.07 (soil temperature) (r^2 = 0.59, $p \leq .001$) (Delucia and Smith 1987).

mature trees of the central Rocky Mountains ranged from about 600-800 mol m^{-2} s^{-1} PPFD, Smith 1985b). Albeit, shade intervals generated by cloud cover could conceivably act to conserve transpirational water via stomatal closure and/or lower leaf temperatures and LAVD. Thus, a longer-term effect on water relations could be to enhance daily or seasonal water status, and, ultimately, seasonal carbon gain.

The shortterm changes in net photosynthesis and leaf conductance under variable sunlight regimes may have a major effect on daily and seasonal carbon gain and water loss. For example, a transition from full sun to cloud shade may cause a rapid decline in photosynthesis while the stomatal response is considerably slower. This would result in a continuation of transpirational water loss at very low photosynthetic carbon assimilation leading to low water use efficiency (mass CO_2/mass H_2O).

Recent investigations on alpine and subalpine plants has demonstrated that considerable differences in the degree of "coupling" between stomatal and non-stomatal responses during multiple sun/shade transitions can result in substantial differences in daily carbon gain and water loss (Knapp and Smith 1987a,b). Several herbaceous species respond to the numerous sun/shade periods (often > 80 per day) by rapidly changing photosynthetic rates as well as stomatal opening. Leaf conductance closely tracks photosynthetic rate resulting in high water use efficiency (fig. 7). In contrast, shrub and tree species including common central Rocky Mountain conifers show very little tracking between photosynthesis and stomatal conductance (fig. 8). In early summer, stomata in the conifers responded very slowly to shade intervals, resulting in relatively poor water use efficiency. However, recovery to previous full-sun photosynthesis after the return of full sunlight appears rapid in conifers. An adaptive response such as this would act to enhance carbon gain at the expense of water conservation. Also, it appears as though the capability in shrub and conifer tree species to maintain a constant and relatively high xylem water potential during full-sun exposure enables stomata to remain open during shade intervals and, thus, insure that

maximum photosynthetic rates are obtained rapidly following the return of full-sun. This maintenance of a high stomatal conductance during shade intervals would favor carbon gain over water conservation. Such a "strategy" might certainly be an advantage in cold-temperature habitats such as the subalpine zone where water may be less limiting than seasonal carbon gain. Whether or not shrub and conifer species show a better tracking between A and g later in summer when water stress is more likely remains a question.

Conclusions

At this time, it is difficult to make accurate quantitative, or even qualitative, predictions concerning the specific environmental parameters limiting photosynthetic capacity in subalpine conifers of the central Rocky Mountains. The complexity of the photosynthetic response (both stomatal and non-stomatal) to an equally complex set of environment variables combine to produce a challenging problem However, approximate estimations based on the data presented here predict that

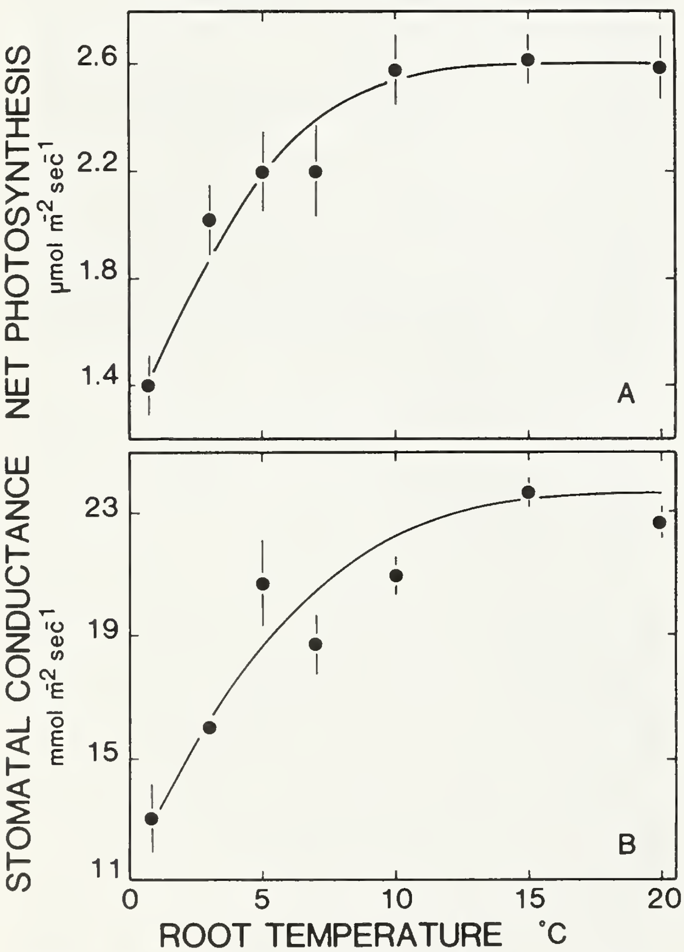

Figure 6.--The effect of different root temperatures and a constant shoot temperature (20 C) on net photosynthesis (A), and stomatal conductance (B) in potted Engelmann spruce seedlings. Curves were fitted by hand. Error bars are 1 SEM, N = 3 (DeLucia 1986).

the following ranking: cloudcover, cold air and soil temperatures, LAVD, and soil moisture could provide a hypothetical order of importance for limitations to seasonal carbon gain. Early and late season appears dominated by cold air temperature limitations while the most important mid-season factors are predominantly soil temperature and LAVD. The specific influence of soil moisture is probably reflected in LAVD responses, increasing the importance of this stomatal response in late season. However, this conclusion is still primarily conjecture and further work is needed to add credibility to this idea as well as the other tentative conclusions expressed above and depicted in table 1 and figure 1.

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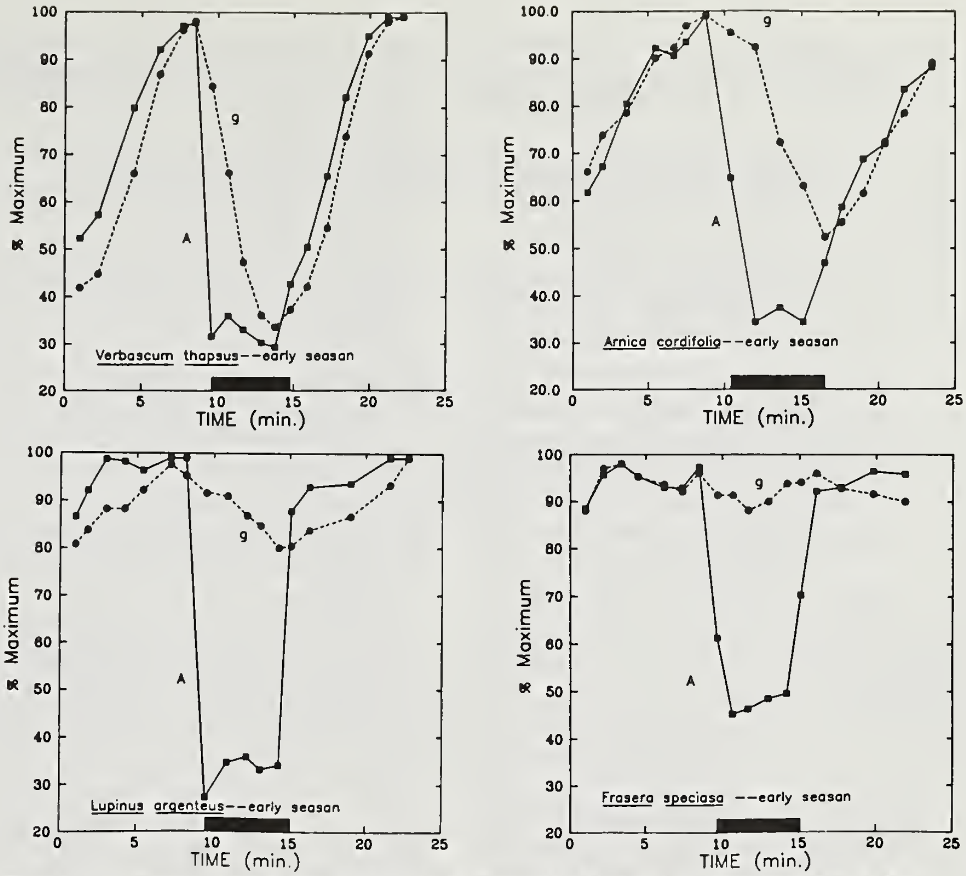

Figure 7.--Coupling of the A and g response in herbaceous species to alternating sun/shade intervals simulating cloudcover. Solid lines are A; dashed lines g.

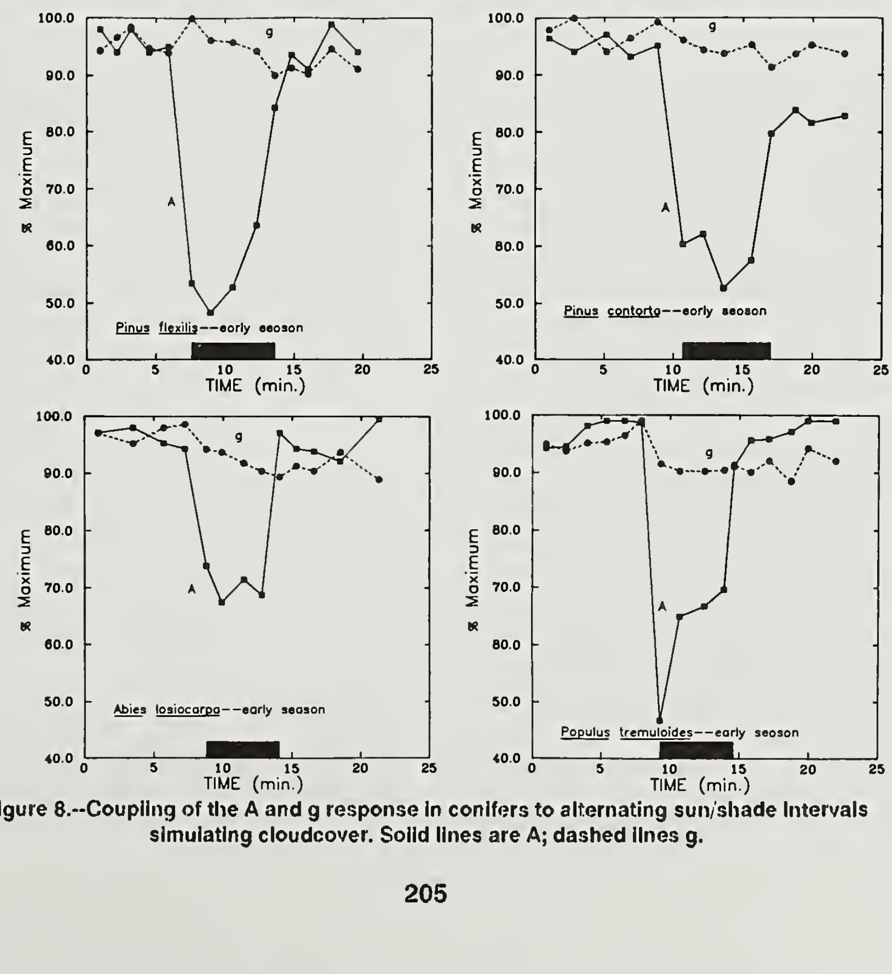

Figure 8.--Coupling of the A and g response in conifers to alternating sun/shade intervals simulating cloudcover. Solid lines are A; dashed lines g.

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Water Uptake of Subalpine Conifer Branches During Heating

W. B. Cohen, P. N. Omi, and M. R. Kaufmann[1]

Abstract--Transpiring pine, spruce, and fir branches were connected to potometers and some were treated with transverse cuts to induce a wide range of transport resistances. The branches then were heated in an oven at 225° C. During heating branches without transverse cuts transported water at significantly greater rates compared to their preheating transpiration rates, and branches which were treated with transverse cuts transported water at lesser rates than branches without transverse cuts.

A wildland fire in which the flames enter the vegetation canopy and consume its fuels is known as a crown fire. Crown fires account for only a small proportion of all forest fires, but because they are often so devastating, they are normally responsible for a disproportionately large share of the annual costs and damages associated with wildfires.

Conifer forests are a common setting for crown fire events. The crown of a live conifer tree consists of an abundance of needles and twigs (fuels) which are continually undergoing changes in their water relations (Chrosciewicz 1986, Fuglem and Murphy 1980, Jameson 1966, Philpot and Mutch 1971, Van Wagner 1967). In the annual water content profile of live conifer fuels there is commonly a period in spring when an apparent water deficiency (stress) is evident. Hough (1973), Van Wagner (1977), and Springer and Van Wagner (1984) have speculated that historical occurrences of conifer crown fire outbreaks in spring is linked to this period of water stress.

The only published results from experiments relating the water status of live conifer fuels to ignitability are by Quintilio (1977) and Van Wagner (1963). In both experiments, severed saplings were subjected to flames in a laboratory and a high correlation was found between foliage water content (expressed as percent dry weight and often referred to as moisture content) and the amount of fuel consumed. For dead fuels, water content may be a good measure of ignitability, but for live fuels both the mass of water and the mass of dry matter are variable (Gary 1971, Pharis 1967). Thus, a measure of live fuel water relations encompassing more than percent water content is probably desirable for assessing ignitability of live fuels.

Water enters and leaves living foliage in response to environmental and plant conditions (Kramer 1983). Rothermel and Susott (pers. comm., 1986)[2] hypothesized that live conifer fuels, when heated, may be capable of drawing upon water stored elsewhere in the tree and thereby forestall ignition. If live fuels have such a capability, a water relations index which is not only independent of dry matter variations, but which also incorporates a measure of water transport, may be a better indicator than water content of a live crown's susceptibility to ignition.

Using standard transport law, studies of water transport into tree foliage and of evaporation of water from the foliage surface have indicated that flow in both cases is regulated by a gradient or driving force and by resistance to flow (Fiscus et al 1983). For water supply to the foliage, the gradient typically is taken to be the difference in water potential between the point of supply and the foliage, and the resistances are those associated with liquid phase flow of water through xylem tissue. For evaporation from the leaf surface, the gradient is a vapor pressure deficit or a vapor concentration difference from leaf to air, and the resistances are those associated with vapor flow from the water surface in the tissue to bulk air outside the foliage.

In the field environment, the rate of water loss from foliage by transpiration is nearly equal to the rate of water transport into the foliage by the xylem. Small differences in these rates during the course of a day contribute to changes in foliage water content and to the development of midday water stress. We suspect that during a fire, foliage tissue rapidly becomes exposed to abnormal conditions in which the vapor gradient increases enormously because of leaf heating. In addition, high temperatures may sharply reduce the resistance of the foliage

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surface to water vapor loss. Under these conditions, evaporation from the foliage surface would increase dramatically. If the rate of water transport into the foliage remains the same as it was before heating, the tissue will dry rapidly, and if the temperature becomes high enough, the tissue will ignite.

Based upon this interpretation, the capacity of tissue to protect itself from ignition depends upon the ability of the transport system to supply water to the foliage. In this study, the role of water transport into tissue exposed to elevated temperatures is related to the initial rate of transport into the tissue and the initial foliage water potential. In addition, visual characteristics of the foliage are related to the transport rate during heating. The results from this study could provide guidelines for the development of an index relating foliage water relations within a conifer canopy to its susceptibility to ignition.

Figure 2.--An assembled potometer. Branch water uptake is measured in the barrel of the uptake measurement syringe. As needed, water transported by the branch is replenished with water from the recharge syringe.

Materials and Methods

During the period from February to June, 1987, freshly cut boughs from three conifer species, lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), were brought to a laboratory weekly and refrigerated in plastic bags. As needed, branches were cut from the boughs and placed in specially designed potometers (figs. 1 and 2). The potometers supplied water to the branches continually and permitted branch transpiration rates to be monitored.

Branches were chosen by species in groups of four. They were selected according to size and health criteria, with the intent of selecting branches which were similar in form and vigor; branch selection was somewhat limited, however, which restricted application of the size criterion. The approximate ranges of length and diameter inside the bark of the branches were between 160 and 240 mm and between 2 and 4 mm, respectively. After attachment to the potometers, branches were allowed to stabilize for one day. To obtain a variety of water stress levels in the branches, on the second day, some branches were given two opposing transverse cuts (after Mackay and Weatherley 1973) to a depth of approximately 70% of their diameters. The separation of the cuts varied between 4 and 7 mm. The intent of the cuts was to inhibit flow and thus cause a decrease in water potential (an increase in stress). The other branches were left untreated. The laboratory environment included diffuse lighting, room temperature of approximately 23° C, and relative humidity which varied between 30% and 45%.

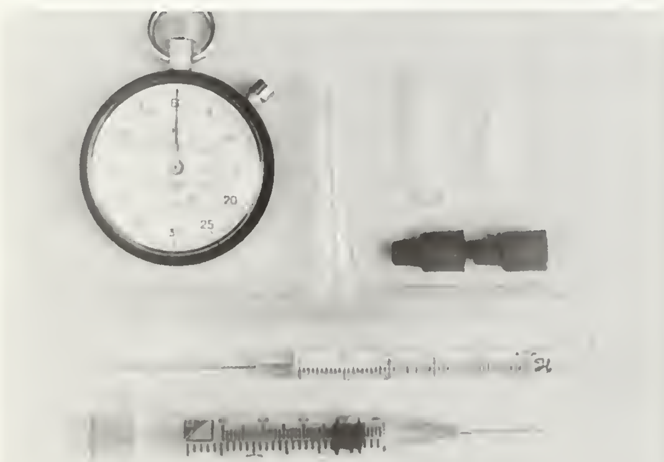

Figure 1.--Potometer used to monitor branch water uptake before and during heating. It includes: (top, left to right) a stopwatch, a glass tee, (clockwise) a short piece of flexible tubing, an automatic pipet tip, two rubber serum stoppers; (middle) an uptake measurement syringe with microliter resolution; and (bottom) a recharge syringe.

On the third day, branch transpiration rates were determined for a 6- to 10-minute interval. Water potentials were measured using a pressure chamber technique; for spruce and fir, branch tips were used (removing less than 10% of the leaf area) and for pine, needle fascicles were selected. Immediately after recording water potentials and transpiration rates, the branches were placed into the exhaust port of a convection oven which was set at a temperature of 225° C, with the potometers supported outside of the oven. Water uptake by the branches during heating was monitored every minute for twenty minutes. A total of 14 pine, 19 spruce, and 24 fir branches were heated. Visual observations during heating were made on 8 branches of each species. Foliage color and surface appearance were noted every minute.

Results

When branches were set up in potometers and given time to equilibrate, their transport rates rarely varied more than 15% per hour. When branches without transverse cuts were

placed in the oven, their water uptake increased substantially. Figure 3 shows the average rate of water uptake for the branches without transverse cuts, during 20 minutes of heating, normalized to the maximum rate during that time. Normalization minimized the effect of variability in leaf area and water potential from branch to branch. Initial transpiration rates prior to heating are shown at minute 0. Prior to heating, pine transported water at only 2% of the maximum uptake rate attained, which occurred around minute 6. Spruce and fir had prior uptake rates of 8 and 19% of maximum, respectively. While actual rates varied widely among species and with branch size, the pattern for normalized rates was similar for all three species when their capacity for flow was not initially inhibited by transverse cuts.

Foliage color during heating changed consistently among species in relation to position on the normalized water uptake curves (figure 3). All branches were green when first placed in the oven and by minute 1 were glistening. Glistening was associated with a decrease in water uptake. After minute 1, the foliage began to turn yellow and lose its glistening appearance. At this time, the rate of water uptake began to increase sharply. As the foliage began turning brown, water uptake quickly leveled off near the peak rate. After brown needles dried and became brittle, water uptake still occurred at rapid rates, declining only to 50% of the maximum in 9 minutes for pine and 13 - 14 minutes for spruce and fir.

Branches which had been treated with transverse cuts increased their rates of uptake during heating compared to their preheating transport rates, but had much lower rates relative to branches without transverse cuts. Figure 4 shows the uptake rates for the cut versus uncut branches for each species. A t test on the peak uptake rates for branches treated with transverse cuts against those without cuts revealed that uptake differences were significant at the .01 level for all species. The lower uptake rates by the cut branches are probably associated with increased resistances to flow from

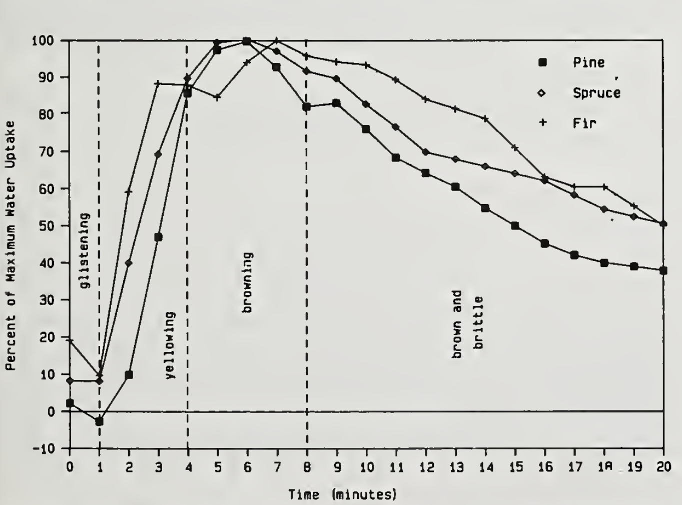

Figure 3.--Rate of water uptake during heating normalized over the maximum rate attained. Average rates for uncut branches, and foliage color changes associated with regions on the uptake curves are shown.

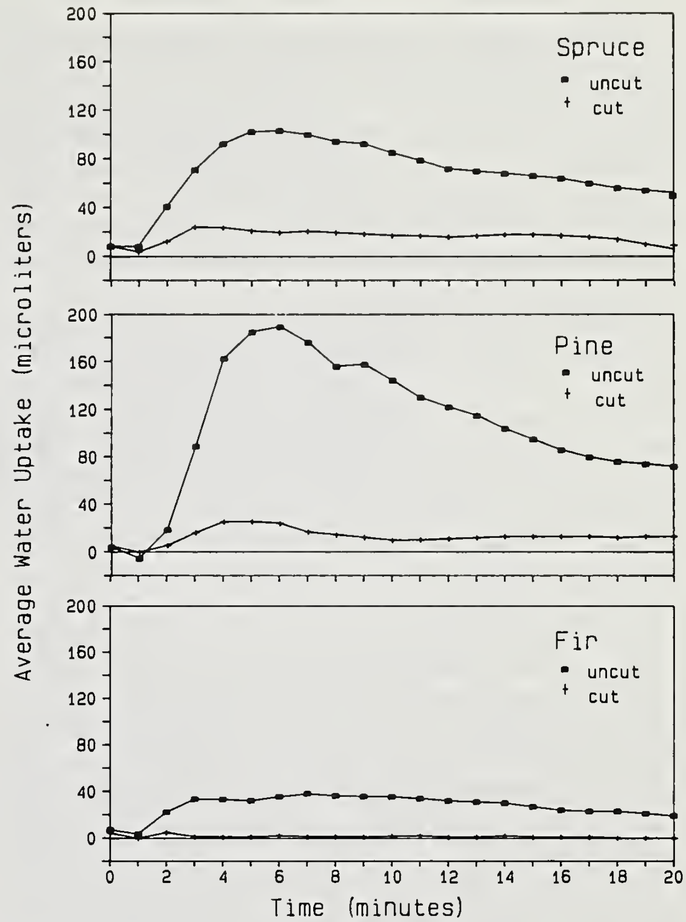

Figure 4.--Average water uptake rates for cut and uncut branches.

the cuts. The progression of color change during heating was generally more rapid for cut than for uncut branches.

In an attempt to determine if water loss from the branch's woody surface also influences water uptake during heating, a few branches of each species were heated just after removing all foliage. Impetus for this came from the fact that uptake continued even after all of the needles on the heated branches became brown and brittle. During heating, all defoliated branches transported water at higher rates than prior to heating, although rates were highly variable. Thus, it appears that the branch surface also may influence the amount of water transported during heating.

Discussion

Pine, spruce, and fir branches increased their water transport rates when heated. On a normalized basis, all 3 species underwent similar rates of change during the full 20 minutes of heating. The capability to increase water transport rates during heating supports the hypothesis that live conifer fuels may be able to draw water from the tree bole during heating and thereby forestall ignition.

On a normalized basis, foliage color changes were associated with changes in rates of water uptake for all three species. Because the progression of color change was more rapid on branches with transverse cuts, it appears that restrictions of water supply during heating also may cause more rapid damage to canopy foliage. Additionally, since the transverse cuts caused reductions in both peak and total water flow, water uptake during heating may be closely related to resistances to flow within the xylem tissue.

Initial foliage water potential prior to heating was not correlated well with water uptake during heating. Part of the reason for this is due to variations in branch size; ie, larger branches generally transport more water than smaller branches, all else being equal. Laboratory conditions also may have contributed to the poor water potential effect. Lighting intensity in the laboratory was low relative to the natural foliage environment. Because of this, foliage stomata probably remained partially closed, inhibiting transpiration, and thereby permitting the maintenance of a relatively high water potential. Although the water potential of branches treated with transverse cuts used in this study was not always lower, the cuts apparently increased transport resistance enough to sharply reduce water uptake during heating. In observations on branches moved temporarily into full sunlight, water potential generally decreased and transport increased. In future experiments, branches will be kept outdoors in more natural lighting conditions for at least an hour prior to heating, and water uptake will be expressed on a unit leaf area or xylem surface area basis. These improvements in technique should help to improve the possibility of discovering if initial water potential is a good indicator of water uptake during heating and/or ignition.

The study reported here will be continued using a specially designed calorimeter which will ignite live branches while measuring the energy required for ignition. The calorimeter will be used both on detached branches connected to potometers and on in situ branches. Experiments on the branches in potometers should permit the development of a relationship between water transported during ignition and the energy required for ignition. Water transported by in situ branches can then be inferred from the measured ignition energy.

A foliage water relations index which incorporates a measure of water transport may be useful in assessing a canopy's susceptibility to ignition. Field studies, using in situ branches, are needed to validate this assertion.

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The Diversity in Streamflow Response from Upland Basins in Arizona

Malchus B. Baker, Jr.[1]

Abstract--Although water yield from a basin is a function of a number of factors, soil depth is considered foremost in explaining hydrograph differences from study areas in Arizona. The most attenuated hydrograph found was in the chaparral vegetation type, which has the greatest soil depth, while the most responsive or peaked hydrographs were found in the pinyon juniper and ponderosa pine types, which have soil depths of 3 feet or less.

In Arizona, most of the 97 million acre feet of precipitation that reaches the soil is returned to the atmosphere and about 3% runs off as streamflow (Hibbert 1979). Nearly all of the water yield in Arizona is derived from 33% of the land area. Water yields range from 0.4 to 5 inches, with the ponderosa pine type contributing 59%, pinyon juniper 27%, chaparral 10%, and mixed conifer 4% of the streamflow.

Water yield is a function of geology, soil, elevation, orientation, vegetation, and climate. All of these factors modify to various degrees the disposition of energy and precipitation falling on an area and, therefore, the quantity of runoff or hydrologic response. The keys to the type of hydrologic response are (1) how far water must travel to influence channel flow, and (2) the mechanism by which it is delivered. Basins in Arizona have a large diversity of controlling factors, and consequently produce a significant amount of variation in streamflow response.

Objectives and Study Area

The objectives of this study were to select hydrographs from basins that demonstrate the diversity in streamflow response found in Arizona, and to identify the major factors responsible for the diversity. These basins include 3 Bar D in the chaparral vegetation type; three basins on the Beaver Creek drainage in the pinyon juniper woodland and ponderosa pine types; and Castle Creek, Thomas Creek, and Workman Creek in the mixed conifer type. Characteristics of these watersheds are presented in table 1. Additional information about these watersheds can be found in Baker 1986, 1984; Hibbert et al. 1974; and Rich and Thompson 1974.

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Streamflow Response

The shape of the hydrograph is an indication of the responsiveness of a basin, and is determined by the delivery rate of water and length of the flow path to the source area. The following spring streamflow hydrographs were produced during the unusually wet water year of 1973. Because of the large range in streamflow response derived from these basins, a wet water year was selected to avoid the potential problems caused by local soil moisture deficits that affect watershed response to precipitation and to snowmelt, and to insure that an adequate amount of streamflow was available for visual comparison of the hydrographs.

Streamflow in figure 1a is from the 3 Bar D chaparral watershed. Parent material is coarse granite. Soil in the basin includes all porous material in which weathering and roots are active, and reaches depths up to 30 feet (Hibbert et al. 1974). Streamflow normally occurs about one third of the time. October precipitation, which normally averages 2.7 inches totaled 14.6 inches in 1972. This unusually wet month resulted in the initiation of continuous flow from the normally ephemeral stream channel that continued throughout the remainder of the water year and on until June of 1974. Spring snowmelt began on February 11 (fig. 1a) at a baseflow level of 0.5 $ft^3\ s^{-1}\ mi^{-2}$ gradually rising to a baseflow rate of 3 $ft^3\ s^{-1}\ mi^{-2}$ on April 5, which then gradually receded back to 0.5 $ft^3\ s^{-1}\ mi^{-2}$ on May 19. Peak discharges during this period were associated with rain on snow events; the first, on February 12, reached 5 $ft^3\ s^{-1}\ mi^{-2}$. Discharge reached a maximum of 9 $ft^3\ s^{-1}\ mi^{-2}$ on March 29. After each precipitation event, the general recession flow level was increased. Normal runoff to precipitation ratio on this basin is 0.13 while the same ratio for water year 1973 was 0.22 (table 1). Of the 11.4 inches of streamflow for the year, 6.4 inches or 56% was produced during the period of February through April.

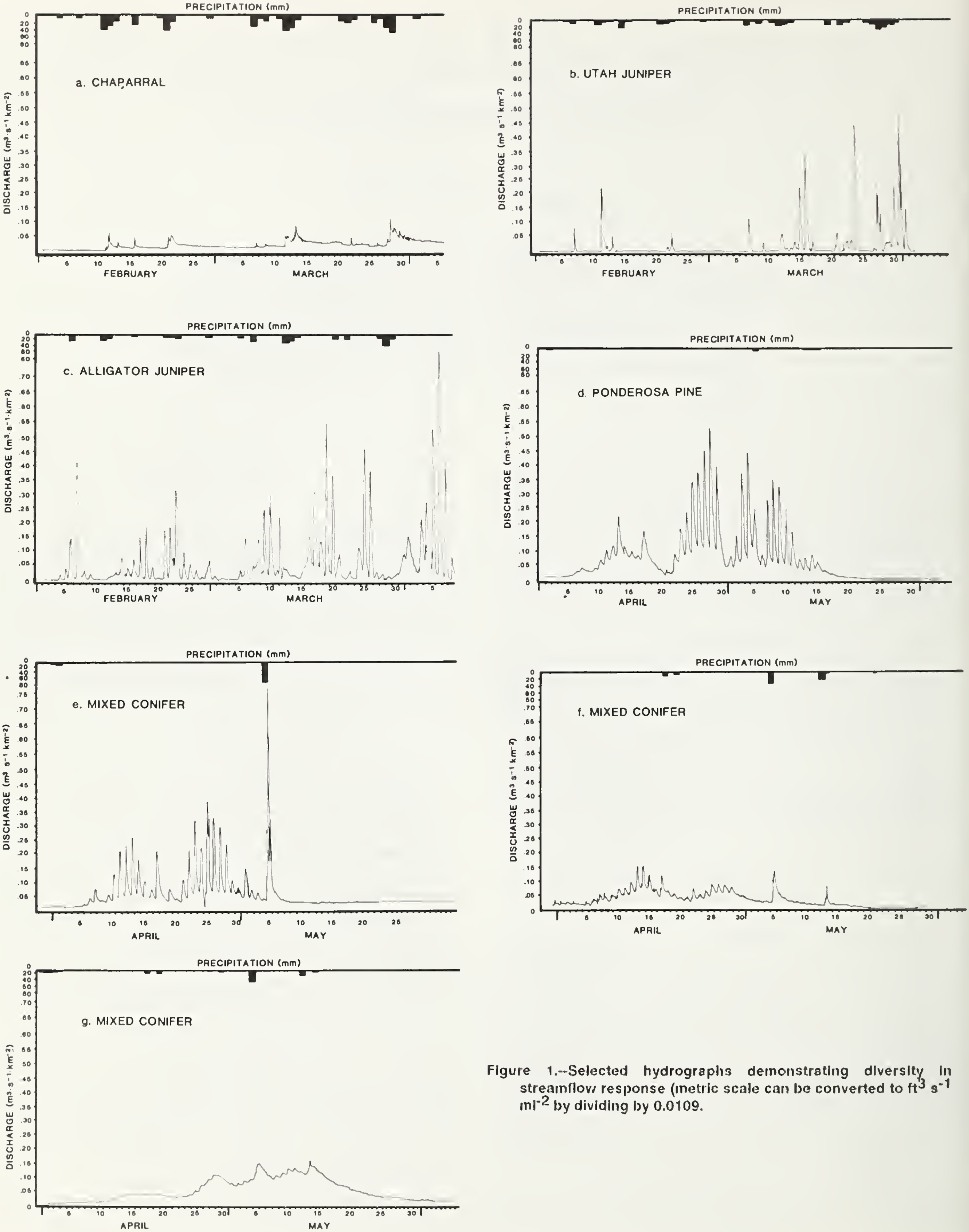

Figure 1.--Selected hydrographs demonstrating diversity in streamflow response (metric scale can be converted to ft^3 s^{-1} mi^{-2} by dividing by 0.0109.

Figures 1b, c, and d are streamflow hydrographs produced in three different vegetation types on the Beaver Creek drainage. Soils on Beaver Creek are developed from volcanic materials, primarily basalt, and depth is generally less than 3 feet. The soil typically has an A horizon that is 0.4 to 6 inches deep. Snow melts in the Utah juniper (fig.1b) during the same time period as in the chaparral type on 3 Bar D (February through April). Streamflow from this basin is much more responsive than from the chaparral basin. Daily discharge peaks are often over 10 $ft^3\ s^{-1}\ mi^{-2}$ and usually return to zero within hours, indicating much faster travel time and shorter flow paths. Saturated overland flow has been observed regularly during spring snowmelt on the Beaver Creek drainage. In water year 1973, measured runoff was 19% of the measured annual precipitation, with 61% of the streamflow occurring during the spring snowmelt period.

At a higher elevation, streamflow fluctuation in the alligator juniper type (Watershed 4) is also very high (fig. 1c). The daily peaks from snowmelt are more numerous and greater than peaks on the Utah juniper or chaparral basins (figs. 1b and a, respectively) reflecting the greater amount of snowpack at the higher elevation and smaller amount of overstory basal area on the alligator juniper basin. The highest peaks during this snowmelt period resulted entirely from snowmelt, reaching 51 $ft^3\ s^{-1}\ mi^{-2}$ on March 19 and 73 $ft^3\ s^{-1}\ mi^{-2}$ on April 6. Although streamflow did not go to zero until April 14, daily lows often approached 1 or 2 $ft^3\ s^{-1}\ mi^{-2}$. Periods of precipitation caused significant declines in flow by reducing incoming energy needed to melt snow.

The snowmelt hydrograph from the basin in the ponderosa pine type (Watershed 8) is almost free of any precipitation events, and was initiated about two months later than on the preceding basins (fig. 1d). Even for this wet year (46.0 inches of precipitation compared to the normal of 26.8 inches) spring snowmelt lasted only 6 weeks. Daily peaks would increase during a warming period, along with a similar increase in the slower subsurface flow component. Streamflow ended on May 29, indicating the reduced water storage capacity of this basin. Although daily peaks were generally greater than on the chaparral basin (fig. 1a), they were usually lower than from the less densely covered alligator juniper basin (fig. 1c). About 32% of the runoff produced during water year 1973 came during the April through May melt period.

The streamflow hydrograph from the mixed conifer type on the South Fork of Workman Creek (fig. 1e) reflects the higher water storage capacity of the basin (perennial streamflow) and overall lower responsiveness (generally lower daily peaks) (fig. 1d). Surface soils are loam to clay loam in texture; subsoil varies in texture from clay loam to clay (Rich and Thompson 1974). Soil depth varies from 2 inches to more than 15 feet. Snowmelt initiation is identical to that on the ponderosa pine basin at Beaver Creek (fig. 1d) but the daily peaks and delayed flow rates are generally not as high. A selection harvest on South Fork removed 46% of the merchantable timber; a second treatment converted the entire South Fork basin to ponderosa pine with 40 $ft^2\ ac^{-1}$ of basal area. This heavy reduction in overstory basal area has allowed more energy to reach the snowpack, resulting in the higher daily peaks from April 5 to 20 than observed on the ponderosa pine basin (fig. 1d). However, daily peaks during the latter part of April were smaller and snowmelt was essentially finished by May 5 on Workman Creek (fig. 1e) while continuing until after May 15 on the pine basin (fig. 1d). Maximum daily discharge peak (derived entirely from snowmelt) reached 35 $ft^3\ s^{-1}\ mi^{-2}$. Snowmelt lasted only 1 month, ending with a major rainfall derived peak of 72 $ft^3\ s^{-1}\ mi^{-2}$ produced by a storm event of 2.7 inches.

Streamflow patterns from the mixed conifer on East Fork of Castle Creek were similar to that on Workman Creek (fig. 1e) but more attenuated (fig. 1f). The Castle Creek area, at a

Table 1.--Physical characteristics of study watersheds.

Characteristics	3 Bar D	Beaver Creek Watershed 2	Beaver Creek Watershed 4	Beaver Creek Watershed 8	Workman Creek South Fork	Castle Creek East Fork	Thomas Creek South Fork
Vegetation type	Chaparral	Utah juniper	Alligator juniper	Ponderosa pine	Mixed conifer	Mixed conifer	Mixed conifer
Size (ac)	82	126	257	1804	319	1164	563
Mid area elevation (ft)	4200	5200	6250	7300	7150	8200	8700
Soil depth (ft)	30	3	3	3	13	<6	<6
Basal area (ft2 ac-1)	751	60	22	130	40	120	180
Annual precipitation (in)	29.5	18.1	20.1	26.8	31.9	25.6	29.1
Annual runoff (in)	3.9	1.2	4.3	6.9	3.5	3.5	3.2
AR/AP	0.13	0.07	0.21	0.26	0.11	0.14	0.11
1973 Precipitation (in)	53.0	26.8	34.4	46.0	62.4	37.0	42.9
1973 Runoff (in)	11.4	5.1	21.1	23.1	22.0	13.8	14.3
R/P	0.22	0.19	0.61	0.50	0.35	0.37	0.33

[1]Percent crown cover.

mean elevation of 8,200 feet, is predominantly covered by ponderosa pine, but is immediately adjacent to the extensive mixed conifer stands in the White Mountains of eastern Arizona. Because of its climatologic and hydrologic similarity to mixed conifer and dissimilarity to much of the ponderosa pine in Arizona, it is considered mixed conifer in this study (Rich and Thompson 1974). Soils are developed from basalt and depths are generally less than 6 feet with a heavy clay layer at 2 feet.

Peak flow and delayed flow increased daily during the warming period that began on April 6 (fig. 1f). Although the daily flow spikes are obvious, they are much less responsive than those on Workman Creek, indicating a higher relative resistance resulting from an integration of a slower water delivery rate and a longer flow path. Daily peaks were usually between 3 and 5 $ft^3 s^{-1} mi^{-2}$ with the highest snowmelt peaks of 14 and 15 $ft^3 s^{-1} mi^{-2}$ on April 13 and 14, respectively. Most snow was lost by the end of April. The streamflow events on May 5 and 14 are dominated by rainfall.

Streamflow from the mixed conifer type on the South Fork of Thomas Creek is often perennial, but occasionally ceases for a 1 or 2 month period. The basalt derived soils are generally less than 6 feet in depth. Streamflow in water year 1973 (fig. 1g) began to rise gradually on April 11, leveling off from April 15 through April 25, and then started to rise again. Daily fluctuation generally consists of a small increase, and then a leveling off until the next daily increase. Streamflow produced by rain on snow is obvious, such as on May 5 and May 13. The storm event on May 13 apparently depleted the snowpack because, after May 14, the hydrograph consisted of a gradual recessional flow which lasted through the end of the month. Although the annual precipitation of 42.9 inches (about 1.5 times normal) produced 14.3 inches of streamflow (4.6 times normal), maximum daily peak discharge only reached 12 $ft^3 s^{-1} mi^{-2}$, excluding any influence of rain events which caused discharge to reach 15 $ft^3 s^{-1} mi^{-2}$.4

Discussion

Although this is a limited set of hydrographs from one wet year (1973), some observations can be made, and one can get a feel for how much the various factors affect streamflow response, and how much these factors can interact in Arizona.

Runoff efficiency rates (ratio of runoff to precipitation) nearly doubled or tripled on all study basins in 1973, showing the influence precipitation can have on streamflow (table 1). The chaparral basin is at the lowest elevation, but receives the second highest average annual precipitation (29.5 inches). This basin had the most attenuated or least responsive hydrograph (fig. 1a), even though it received the second highest amount of precipitation (53.0 inches) in 1973. It also has the deepest soil (30 feet). Similar chaparral basins have been shown capable of producing perennial flow once the chaparral overstory is converted to grass, suggesting the influence of soil depth on the storage of precipitation and its eventual release (Hibbert et al. 1974).

The most responsive or peaked hydrographs occurred on the Beaver Creek drainage area with a mean soil depth of about 3 feet. The Utah juniper basin receives the lowest mean annual precipitation amount (18.1 inches). However, the influence of the soil depth and the relatively impermeable B horizon seems apparent in the highly responsive daily streamflow peaks (fig. 1b). Daily peak discharge rates, even from snowmelt, are relatively large and recede rapidly (in hours), which suggests a relatively small soil water storage capacity and short flow paths (overland flow and shallow subsurface flow).

Streamflow from the alligator juniper basin was similar to the Utah juniper basin, but the higher elevation, higher annual precipitation, and lower overstory basal area produced more numerous and higher daily peaks (fig. 1c).

The ponderosa pine basin on Beaver Creek has similar soil characteristics and similar responsive daily peaks (fig. 1d). However, its higher elevation apparently resulted in a delay of the snowmelt of about 2 months (from February to April). This basin has the highest long term runoff efficiency of the 7 study basins (0.26) and the second highest for the 1973 water year (0.50). Daily peaks were usually lower than on the alligator juniper basin, probably due to the influence of the less dense overstory basal area on snowmelt rates. Flow on the three Beaver Creek watersheds generally terminates within a few days of the disappearance of the snowpack, while streamflow often lasts longer on the other study sites. Even watersheds in the chaparral type, generally considered a dry vegetation type, can produce perennial flow after conversion of shrubs to more shallow rooting species, such as grass (Hibbert et al. 1974). The streamflow hydrographs from Beaver Creek also exhibit the greatest range in daily peaks and the largest range in mean annual streamflow (1.2 inches with 18.1 inches of mean annual precipitation to 6.9 inches with 26.8 inches of precipitation) (table 1).

Annual precipitation at the mixed conifer basin on Workman Creek is highest of the 7 study basins (31.9 inches), and streamflow is normally perennial. Hydrograph responsiveness is similar to that on the ponderosa pine basin, but daily peaks are higher in the beginning of the melt period and lower towards the end suggesting the influence of the heavy reduction in overstory basal area on snowmelt rates (fig. 1e).

Streamflow in the mixed conifer on Castle Creek is similar to that on Workman Creek, but is less responsive or more attenuated, probably as the result of the influence of the higher elevation (8,200 feet) on snowmelt rates (fig. 1f). Daily snowmelt peaks are still recognizable on Castle Creek but greatly reduced. Annual precipitation and overstory basal area are similar to that on the ponderosa pine basin, but the long term runoff efficiency ratio is only about one half as much (0.14 versus 0.26).

The mixed conifer type on Thomas Creek is located at the highest elevation (8,700 feet) and receives the second highest annual precipitation amount (29.1 inches). Daily snowmelt peaks are barely apparent, indicating much more resistance or longer flow distance to the channel. Overland flow or evidence

of overland flow has seldom been observed on the mixed conifer basins. Mean annual streamflows on these 3 basins are relatively uniform (3.2 to 3.5 inches) even though mean annual precipitation ranges from 25.6 to 31.9 inches. Although some attenuation of the hydrographs on the two higher mixed conifer basins is the result of lower snowmelt rates, the high annual precipitation amounts, longer streamflow period, and lower runoff efficiencies suggest that the major factor is the influence of soil depth and texture.

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Commandra Blister Rust: A Threat to Lodgepole Pine

Brian W. Geils and William R. Jacobi[1]

Abstract--Comandra blister rust is an important canker disease of lodgepole pine in the central Rocky Mountains. Current research is quantifying the risk of serious disease outbreaks and the magnitude of resulting losses. Rust incidence in lodgepole pine stands is related to the distance and direction from the alternate host and average tree height. Projected losses are influenced by both stand and disease conditions such as percent of trees infected and average canker height.

Comandra blister rust *(Cronartium comandrae)* causes stem and branch cankers on several species of pines, including lodgepole pine (Johnson 1986). These cankers are resinous areas which produce orange spores that spread the fungus to an alternate host, but not to other pines. Eventually, a canker girdles the host stem, killing all or part of the crown.

Comandra blister rust occurs throughout most of North America, and is a serious cause of loss in many lodgepole pine forests, especially in the central Rocky Mountains. For example, more than half of the lodgepole pine basal area is in infected trees on the Wind River District of the Shoshone National Forest (Geils and Jacobi 1984).

Comandra blister rust has a complex life cycle with five different spore stages produced alternately on two hosts -- a hard pine and the perennial herb for which the fungus is named, pale comandra *(Comandra umbellata)*.

Objectives

The purpose of this cooperative effort was to develop management tools for predicting:

1. Risk of serious disease outbreaks in stands of lodgepole pine in the Rocky Mountains.
2. Magnitude of damage-related losses to forest resources.

Predicting Risk

Although millions of rust spores are produced annually on each diseased comandra plant, only a few of these spores are likely to infect and subsequently cause damaging cankers on the lodgepole pine host. A risk rating system provides the means to estimate the probability of a rust infestation occurring in a given stand during a fixed period.

A few biological factors are important for determining risk. First, the spores that infect the pine are produced only on comandra plants. These plants occur in sagebrush communities at various distances from the pine stands. The delicate rust spores are wind-dispersed from the comandra plants to pines during rainy days in late summer. And finally, the primary infection sites on pines are young, succulent shoots and needles (Krebill 1968).

We are using historical and on-site weather data to determine the frequency of weather events optimal for spore dispersal and pine infection. These data also provide information on wind direction and speed during spore flight.

The distribution of both host species, disease incidence, and patterns of wind flow are being mapped for the southern portion of the Laramie District, Medicine Bow National Forest, in southeast Wyoming. The lodgepole pine on this district is bordered on the east and west by plant communities in which pale comandra occurs.

Within the narrow range of available stand ages, inventory data for lodgepole pine are being analyzed to correlate stand and site conditions (density, height, age, crown size, site index, habitat type) with disease incidence and severity. Together with location and weather data, this information is being used to predict the gradient of disease intensity and to classify sites for risk of infection.

Our preliminary results indicate that:

1. Pine stands as far as 8 miles from comandra plants can be seriously infected.
2. Spore dispersal from comandra plants to pines seems to be associated with easterly winds during long, rainy periods.

[1]Geils is a Research Plant Pathologist with the Rocky Mountain Forest and Range Experiment Station. Station headquarters is in Fort Collins, in cooperation with Colorado State University. Jacobi is Associate Professor of Plant Pathology, Colorado State University, Fort Collins.

3. Disease incidence increases with average tree height.

Predicting Damage

The growth and yield program RMYLD (Edminster 1978) has recently been modified to account for the effects of comandra blister rust on growth, survival, and merchantable volume of lodgepole pine. Projections from this program can be used to predict the extent of damage resulting from a single infection episode. In the following example, damage is illustrated as loss of merchantable volume in a diseased stand in comparison to a similar healthy stand.

A typical lodgepole pine stand in the Rocky Mountain Region (age 40, site index 60 feet) would contain about 715 trees per acre with an average diameter of 4.4 inches and an average height of 27 feet. Without rust or thinning, the RMYLD program predicts the stand would produce 1070 cubic feet in 700 trees (dbh 5.9 inches) at age 60. The yield predictions suggest that the volume loss (due to tree mortality and growth reduction in surviving trees) by age 60 would depend mainly on the percentage of trees infected at age 40:

20% of trees infected = 5% reduction in stand volume.

40% of trees infected = 20% reduction in stand volume.

60% of trees infected = 40% reduction in stand volume.

80% of trees infected = 60% reduction in stand volume.

Average canker height has an effect on average diameter: low cankers kill infected trees quickly, reducing competition, and improving the individual growth of remaining trees. On the other hand, high cankers kill fewer trees but leave the stand overstocked.

Future Work

Given a different set of initial conditions, losses to comandra blister rust would change from those shown above. Additional work is in progress to project losses with more frequent infection episodes in stands of various site, age, and stocking conditions, and subject to a variety of management practices.

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245 Sanitation Thinning in Young, Dwarf Mistletoe-Infested Lodgepole Pine Stands

Frank G. Hawksworth, David W. Johnson, and Brian W. Geils[1]

Abstract--A study was begun in 1965 to evaluate sanitation and thinning in young mistletoe-infested lodgepole pine in northern Colorado. After 21 years, the average dwarf mistletoe rating of the treated plots was less than one-fourth that on the untreated plots. Stand projections suggest that in 20 years the merchantable cubic foot yields on the treated plots will be more than three times that on the untreated plots.

Dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) is the the most serious tree disease agent of lodgepole pine in the Rocky Mountains. This parasite occurs on more than half of the 2 million acres of commercial lodgepole pine forests in the Central Rocky Mountains, and causes an annual volume loss of more than 15 million cubic feet. Dwarf mistletoes are one of the few forest diseases that can be effectively controlled by silvicultural means (Johnson and Hawksworth 1985). However, some early cultural practices actually intensified the problem. For example, harvest operations that left infected residual trees provided ideal conditions for maximum spread and intensification of the disease into young stands.

Thousands of acres of lodgepole pine in the Rocky Mountain Region were partially logged in the 1950's and 1960's and many mistletoe-infected but non- merchantable trees were left standing. These trees now provide a serious source of infection for the young, naturally regenerated stands that have become established beneath them. Sales contracts now call for removal of all infected trees in cutting areas, but vast problem areas of infected reproduction remain in older sale areas.

Study Objectives

The objectives of this joint Rocky Mountain Station-Rocky Mountain Region study are to determine whether young, mistletoe-infested stands can be sanitized and thinned to effectively increase timber yields.

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Methods

Thirty-seven, 1/2 acre plots in 20-, 30-, and 40- year old stands with various intensities of dwarf mistletoe infection were established on the Routt, Arapahoe, and Roosevelt National Forests in 1965 (Hawksworth et al. 1977). Infected overstory trees were removed from each plot. Then about half the plots were sanitized in 1965 and 1968 by cutting all visibly infected trees. These plots, and some mistletoe-free ones, were thinned in 1970 to a 10 X 10 foot spacing (approximately 425 trees per acre). Plots have been remeasured at about 5-year intervals; here we summarize the results after 21 years.

Results and Discussion

Because they present a larger target area for intercepting mistletoe seeds, the larger trees in a stand are typically attacked first (Wicker and Shaw 1967). In this study, the infected trees in 1965 averaged about 1 inch larger in diameter and 3 feet taller than uninfected trees in the same plots. Thus, removing the infected trees initially lowered stand diameter and height.

Before treatment in 1965 the mean stand diameters on treated and untreated plots were essentially the same. In 1970, after sanitation and thinning, the mean diameters on the treated and untreated plots were still about the same because diameter reduction due to removal of the larger, infected trees by sanitation was offset by the removal of smaller, suppressed trees by thinning. By 1986, mean stand diameter for treated plots was 1.7 inches larger than for untreated plots. Simulations from the RMYLD growth and yield program (Edminster 1978) project, that in another 20 years, the mean tree diameter on the treated plots will be 2.5 inches greater than that on the untreated plots.

The proportion of trees infected in untreated plots increased from 28 percent in 1965 to 53 percent in 1986. In treated plots, 30 percent of the trees were infected in in 1965; this level was reduced to essentially zero as all visibly infected trees were removed in 1965 and 1968. In 1986, 26 percent of the trees were infected, or less than half that in the untreated plots.

Differences in ratings of average stand dwarf mistletoe intensity (6-class DMR system, Hawksworth 1977) between untreated and treated plots from 1965 to 1986 were even more marked: stand DMR increased from 0.6 to 1.4 in the untreated plots, whereas it fell from 0.6 to 0.3 in the treated plots. Such low levels of infection on treated plots will result in little effect on tree growth for several decades.

Projections using the RMYLD growth and yield simulation program suggest that volume growth in treated stands will be much greater than that in the untreated stands. For example, the treated stands will produce an estimated 2320 merchantable cubic feet per acre in 60 years, compared to a projected 680 merchantable cubic feet per acre in the untreated stands. These preliminary results confirm that sanitation and thinning can significantly increase yields in young, mistletoe-infested lodgepole pine stands.

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245 Long-Distance Dispersal of Lodgepole Pine Dwarf Mistletoe 4

Frank G. Hawksworth, Thomas H. Nicholls, and Laura M. Merrill[1]

Abstract--A total of 721 birds and 290 mammals were captured at the Fraser Experimental Forest during the autumns of 1982, 1983, and 1986 and examined for seeds of *Arceuthobium americanum*. Eighty one mistletoe seeds were found on 75 trapped animals of 14 species (10 birds and 4 mammals). The gray jay and least chipmunk were the most common transporters of seed. During the peak period of seed dispersal in 1982, 22% of the individual birds and 20% of the individual mammals carried mistletoe seeds. In a 70-year-old stand of lodgepole pine that was otherwise mistletoe-free, we found 1.7 isolated infection centers per hectare, concentrated primarily near large stand openings. Such openings are apparently attractive habitats for birds that may transport dwarf mistletoe seeds for long distances. Thus, there is some evidence that these animals are vectors of dwarf mistletoe seeds, and that they are occasionally responsible for long-distance spread of the parasite.

Dwarf mistletoe seeds are primarily dispersed by an explosive fruit mechanism that projects them for up to several meters (Hawksworth and Wiens 1972). Many observations, however, suggest that dwarf mistletoe seeds are sometimes transported over greater distances than can be explained by explosive fruits (Nicholls et al. 1984). There are a few quantitative studies on dispersal of dwarf mistletoes by birds: *Arceuthobium pusillum* on black spruce *(Picea mariana)* in Minnesota (Hudler et al. 1974 and Ostry et al. 1983) and *A. vaginatum* subsp. *cryptopodum* on ponderosa pine *(Pinus ponderosa)* in Colorado (Hudler et al. 1979).

Hudler et al. (1979) studying dispersal of *A. vaginatum* subsp. *cryptopodum* on ponderosa pine in central Colorado, found 32 isolated ("satellite") centers in 194 ha of otherwise mistletoe-free forest (0.16 centers/ha). Satellite centers contained from 1 to 175 infected trees covering 0.3 ha. The most isolated center was 450 m from the nearest potential seed source.

Ostry (1978) examined black spruce stands infested with *A. pusillum* in northern Minnesota. He found 12 satellite centers in 188 ha of otherwise mistletoe-free forest, or 0.06 centers/ha. The centers contained from 1 tree to more than 100 trees covering 0.15 ha. The most isolated center was 250 m from the nearest potential seed source.

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To better understand long distance dispersal of dwarf mistletoe seeds, we conducted two studies on lodgepole pine dwarf mistletoe *(Arceuthobium americanum)* at the Fraser Experimental Forest near Winter Park, Colorado. Our objectives were to: (1) identify potential avian and mammalian vectors[2] of dwarf mistletoe seeds; and (2) determine the distribution of isolated infection centers in a lodgepole pine stand that was otherwise disease-free.

Methods

Seeds on Animals

This study was conducted during August and September (the period of seed dispersal for *Arceuthobium americanum*) of 1982, 1983 and 1986. Detailed methods appear in Nicholls et al. (1984). The lodgepole pine forest studied is mainly of the *Abies lasiocarpa/Vaccinium scoparium* habitat type. Birds and mammals were captured with cell traps or mist nets, examined, and the number and location of seeds adhering to their bodies recorded (Nicholls et al. 1984). Seeds were tested for viability with tetrazolium chloride (Scharpf 1970).

Birds were banded and mammals were ear-tagged so that individuals could be identified upon recapture. Movements of animals within the study area were monitored by retrapping, color marking, or radio telemetry (Nicholls et al. 1984).

[2]We use the term "vector" as "an animal able to transmit a pathogen" (D. L. Hawksworth et al. 1983).

Timing of dwarf mistletoe seed dispersal throughout August and September was monitored by making daily seed counts on muslin seed traps placed on the ground near infected trees at three different elevations (9,000, 9,400 and 10,200 feet). These seeds were also checked for viability using the TTC test.

Satellite Centers

A 145-acre (58.7-ha) study area in the *Abies lasiocarpa/Vaccinium scoparium* habitat type was examined for satellite infection centers. The stands were mostly even-aged, large pole (20-40 cm d.b.h.), lodgepole pine about 70 years old that originated after severe fires in about 1910. The area contained a few remnants of the original old-growth lodgepole pine, with scattered stands dominated by aspen *(Populus tremuloides)* or Engelmann spruce *(Picea engelmannii)*. The area was examined on a 1 chain (20 m) grid. At each point, lodgepole pines within a 1/2-chain (10 m) radius were examined for isolated infected trees.

In most cases, satellite centers were more than 20 m from the closest seed source. In four cases, however, infection centers were less than 20 m away from the closest seed source but they were considered to be satellites because there were non-infected screen trees between them and the nearest infection source. In all cases where satellite centers were found, there were no stumps of remnant trees that could have provided an infection source.

When satellite infection centers were found, the following data were recorded:

1. Distance and direction to closest potential seed source.
2. Stand structure surrounding the center: (1) within stand (no opening), (2) small opening = no trees in less than 1/3 of the sector of a 10 m radius circle around the center, or (3) large opening = no trees in more than 1/3 of the sector.
3. Number of infected trees.
4. Dwarf mistletoe rating (6-class system; Hawksworth 1977).

The infection that appeared to be the oldest in each center was examined in the laboratory to determine the approximate date of origin based on detection of mistletoe sinkers or xylem stimulation (Scharpf and Parmeter 1966).

The distribution of satellite centers was analyzed using the Raleigh test for concentration, as outlined by Batschelet (1965).

Results

Seeds on Animals

A total of 721 birds (including retraps = IRT) of 31 species and 290 mammals (IRT) of four species were captured. Of these, 10 bird and 4 mammal species had seeds of A. americanum on their bodies (table 1): 29 dwarf mistletoe seeds were found on the fur of 29 mammals and 52 seeds were found on the feathers of 46 (fig. 1). The most common bird species with seeds on its feathers was the gray jay (3 times more seeds than the next closest species); the least chipmunk was the most common mammalian transporter of seed, with over eight times more seeds on its fur than the next closest species. During a 16-day period in 1982 when seed dispersal was at a maximum, 22 percent of the birds (N = 55 IRT) and 20 percent of the mammals (N = 80 IRT) captured had seed.

Five gray jays radio-tracked in 1983 frequently moved back and forth between infected and healthy stands of lodgepole pine. Some of these birds were known to have seeds on their feathers when they were radio-tracked. Details on gray jay movements and home ranges will be discussed in a subsequent paper.

Birds were not observed eating mistletoe seed; rather, they acquired seed when foraging for food in infected trees when seeds were being explosively discharged. The seeds, sticky with viscin, easily stuck to feathers. Most seeds were found

Table 1.--Animals captured at the Fraser Experimental forest and found to have seed of A. americanum in their fur or feathers.

Animal species with seed	Number trapped and examined	Number with seed	Number of seed
Gray Jay (Perisoreus canadensis)	162	22	25
Steller's Jay (Cyanocitta stelleri)	29	5	8
Mountain Chickadee (Parus gambeli)	88	5	5
Gray-headed Junco (Junco hyemalis)	123	3	3
Audubon.s Warbler (Dendroica coronata)	62	3	3
American Robin (Turdus migratorius)	35	2	2
Northern Saw-whet Owl (Aegolius acadicus)	9	2	2
Hermit Thrush (Catharus guttatus)	75	2	2
Three-toed Woodpecker (Picoides tridactylus)	9	1	1
Townsend's Solitaire (Myadestes townsendi)	4	1	1
Ten bird species	596	46	52
Least Chipmunk (Eutamias minimus)	254	24	24
Golden-mantled Squirrel (Citellus lateralis)	20	3	3
Red Squirrel (Tamiasciurus hudsonicus)	15	1	1
Pine Marten (Martes americana)	1	1	1
Four mammal species	290	29	29

around legs, on the breast, and under wings and tail. Of 20 seeds tested with TTC, 65 percent were viable.

Both resident and migratory birds (Alexander et al. 1985) were captured with seeds on their feathers. Of the 10 birds with seed, only 3 (gray jay, mountain chickadee, and three-toed woodpecker) are year-round residents. This suggests that seeds could be disseminated over short distances by resident birds and over long distances by migratory birds.

Birds were not observed feeding on mistletoe plants, but one least chipmunk was seen feeding on dwarf mistletoe fruits for about 20 minutes; subsequently it was seen to have 5 seeds on its fur.

During 1983, when the seed dispersal was measured on traps at 9,000, 9,400 and 10,200 feet, the overall seed dispersal period lasted about 6 weeks and began at the lowest elevation in mid-August. At each site, seed dispersal lasted about 4 weeks, and the peak dispersal was about a week later for each increase of about 500 feet in elevation. Based on TCC tests, 65% of the seeds sampled (N= 66) from the traps were viable, the same percentage as for seeds found on animals.

Figure 1.--Dwarf Mistletoe seed sticking to the (A) tail feather of a Steller's jay, (B) tail of a least chipmunk.

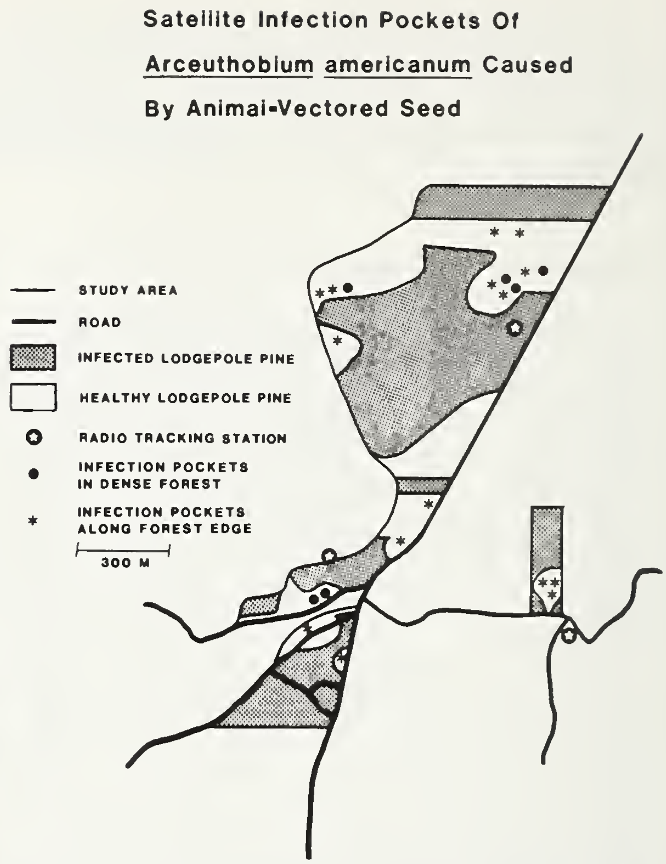

Figure 2.--Satellite infection pockets of Arceuthobium americanum such centers presumably developed from animal-dessiminated seed, Fraser Experimental Forest, Colorado.

Satellite Centers

A total of 1,450 plots were established. Of the 58.7 ha area surveyed, 8.8 ha were not in lodgepole pine (aspen, Engelmann spruce, or non-forest). Of the 49.9 ha lodgepole pine area, 35.3 ha were in stands generally infested by mistletoe. A total of 361 plots fell in the 14.6 ha. of primarily mistletoe-free lodgepole pine where, 25 satellite infection centers were found (fig. 2). Of these, 4 contained infected trees that predated the establishment of the 70-year old stand, but 21 centers (1.4/ha.) were younger than the age of the stand (table 2).

Satellite infection centers ranged from 12 to 65 m (average 27 m) away from the closest potential sources of inoculum. The centers had from 1 to 10 trees (average 3.5) and infection intensity was generally light, with dwarf mistletoe ratings of 1 to 3. The Raleigh test for concentration (Batschelet 1965) showed no significant trend for direction to the closest potential seed source. However, there was a tendency for satellite centers to become established at the edge of large stand openings: 11 of the 21 centers were adjacent to such natural stand openings or along old phone line clearings or logging roads:

Table 2.--Characteristics of 21 dwarf mistletoe satellite centers in a lodgepole pine stand at Fraser Experimental Forest, Colorado.

Satellite no.	Infected trees (no.)	Aver. DMR of infected trees	Distance to closest seed source	Direction to closest seed source	Degree of stand opening*	Age of oldest infection (years)
1	1	1.0	29.0	WNW	1	8
2	1	1.0	12.2	NW	1	19
3	6	1.3	42.0	NW	3	17
4	1	3.0	13.7	NE	3	8
5	2	1.0	21.3	W	1	20
6	5	1.2	28.0	SSW	2	13
7	4	1.3	47.3	WSW	3	14
8	1	1.0	25.0	NE	2	4
9	3	1.0	26.2	N	1	17
10	10	2.3	23.2	N	2	43
11	4	2.0	14.9	NE	3	28
12	1	1.0	20.1	N	2	13
13	2	1.0	65.2	NNE	1	20
14	2	3.0	64.0	S	3	50
15	1	1.0	17.4	NE	3	18
16	8	1.1	35.1	N	1	27
17	9	1.9	33.5	SW	3	39
18	6	1.2	39.3	W	3	20
19	7	1.7	53.4	ESE	3	22
20	10	1.2	43.3	NNE	3	34
21	3	1.0	25.3	E	3	19
Mean	3.5	1.4	32.3	-	-	22

1 = within stand, 2 = small opening, 3 = large opening.

	Number of satellite centers
Within stand	6
Small openings	4
Large openings	11
Total	21

The age of the oldest infection found in each center ranged from 4 to 50 years, but most were between 11 and 20 years old:

Oldest infection (years)	Number of satellite centers
4-10	3
11-20	12
21-30	2
31-40	2
41-50	2
Total	21

No relationship was found between the age of satellite centers and the distance to the nearest potential seed source.

Discussion

There are several reports of dwarf mistletoe infection centers that originated from other than explosively discharged seeds, and are not remnants of fire escapes (Hawksworth and Wiens 1972). These observations have elicited much speculation as to the factors responsible for long-distance spread. Dissemination by birds or animals would explain the origin of satellite infection centers far removed from main infection centers. That these animals may serve as vectors is logical because the seeds will generally stick to anything they hit. Animals can come in contact with mistletoe seeds when foraging for insects, eating mistletoe shoots or fruits, storing food, or nesting in mistletoe brooms. Furthermore, dwarf mistletoe seeds removed during the animals' regular grooming can cause infection if the seeds are viable and deposited on susceptible parts of host trees.

For animals to transport dwarf mistletoe seeds and establish new infection centers and thus serve as vectors, certain criteria must be met (adapted from Zilka and Tinnin 1976): (1) the seed must become attached to the animal; (2) the seed must arrive in viable condition on a susceptible host; (3) the seed

must come in contact with susceptible parts of the host; and (4) both male and female plants must become established; or, if only female plants, they must be close enough to male plants to receive pollen.[3] Because of these specific requirements, mistletoe infections arising from animal-disseminated mistletoe seed are probably infrequent. The scattered cumulative infections that develop over long periods of time, however, coupled with the spread of seeds from the explosive fruits after the centers are established, may occur frequently enough to be of concern in the effective control of this parasite.

This study has documented that animals can transport dwarf mistletoe seeds, and at least two studies (Hudler et al. 1979, Ostry et al. 1983) have shown that birds can inoculate susceptible trees. Thus, these studies indicate that animals can serve as vectors for dwarf mistletoe. The movements and behavior of the different species play a key role in how and where dwarf mistletoe seed is transported. In general, most birds do not eat mistletoe seeds, or, if they do, the seeds are not passed through the digestive tract in viable condition (Hudler et al. 1979, Zilka and Tinnin 1976, Ostry et al. 1983). All studies to date show that viable dwarf mistletoe seeds are transported only on the external surfaces of animals.

The distance seeds can be transported by animals depends on their home range size is and whether they are migratory or resident. Because of their relatively small home ranges, mammals are probably important only in local spread and intensification. Resident birds, such as the gray and Steller's jays, mountain chickadees, and gray-headed juncos, would also be most important in local and short-distance spread of dwarf mistletoe. This study and others (Hudler et al. 1974, Ostry et al. 1983) found the gray jay to be the most common vector of mistletoe seeds.

Migratory birds, such as the warblers (*Dendroica* spp.), robin, and hermit thrush, may be more important in long-distance spread of dwarf mistletoes. Many dwarf mistletoe species release seed during late summer and fall when these birds are migrating southward. Because birds that select a lodgepole pine habitat in one area may choose the same habitat in other areas during migration, seeds picked up in an infected stand could be deposited in a similar stand some distance away. This habitat specificity is important and increases the chance that a successful infection will result, because dwarf mistletoes are generally host specific (Hawksworth and Wiens 1972).

Least chipmunks and golden-mantled squirrels spend most of their time on the ground, where they probably picked up seeds already released from the fruits. In contrast, red squirrels spend proportionately more time in the trees cutting down cones and storing mushrooms in dwarf mistletoe witches brooms and other branches. They were frequently seen brushing against mistletoe shoots during these activities. In contrast to the birds in this area, the home ranges of these mammals is small, so they may be involved only in local dissemination of dwarf mistletoe.

Highly specific requirements must be satisfied before a successful dwarf mistletoe infection can occur. Once infection occurs, several years must pass before the life cycle of the pathogen can be completed to establish an infection center. Because of these highly specific requirements, infections that develop from animal-disseminated seed are probably infrequent. The cumulative establishment of scattered infection centers over long periods of time, however, and subsequent local dispersal, can accelerate and intensify the spread of dwarf mistletoes.

The number of satellite centers (1.4 per ha) found in this study is greater than that reported for other dwarf mistletoes (Hudler et al. 1979, Ostry 1978), and suggests that long-distance dispersal in lodgepole pine may be more common than has been generally recognized.

A factor that may tend to favor animal dispersal of mistletoe in lodgepole pine is that host tissues up to 60 years old are susceptible to infection by *A. americanum* (Hawksworth 1954). This age is in marked contrast to most dwarf mistletoe hosts, where infection typically takes place only through tissues less than 5 years old (Hawksworth and Wiens 1972). A possible result is that larger animals may serve as vectors, since potential seed transport would not be limited to young, needle-bearing tissues. For example, only small birds (chickadees and nuthatches) are implicated as vectors of *A. vaginatum* on ponderosa pine (Hudler et al. 1979), where most infection occurs on needle-bearing twigs 1-3 years old (Hawksworth 1961).

Most of the satellite centers were from 11 to 20 years old; thus they became established when the stands were from 50 to 60 years old. This age distribution supports our observations that satellite centers are rather rare in young (less than 50-year-old), even-aged stands of lodgepole pine established in clearcuts or regenerated burns. Taylor and Barmore (1980) studied the avifauna in relation to post-fire succession in lodgepole pine in Yellowstone and Grand Teton National Parks, Wyoming. They found marked variation in bird activity with time since the initial burn:

Years after fire	Activity
1-4	Intense bird activity, particularly woodpeckers in trees killed by the fire.
5-30	Very little bird activity; only white-crowned sparrows abundant.
30-50	Bird activity greatly increased, about 13 species are common.
50-100	Species guilds about the same as at 30-50 years, but lower density. Gray jays, not listed at 30-50 years, now common.

[3]The effective distance of pollen dispersal in the dwarf mistletoes has not been determined, but pollen dispersal distances for A. americanum of 510 m have been reported in Colorado (Copolla, in press) and 400 m in Manitoba (Gilbert and Punter 1984).

Studies in Colorado confirm that there are few birds in young lodgepole pine stands (Hein 1980, Mullis 1978). Gray jays, and to a lesser extent Steller's jays and mountain chickadees, were the main bird species transporting seeds of lodgepole pine dwarf mistletoe at the Fraser Experimental Forest. The above studies suggest that these species find young stands in clearcuts or burns (younger than 30-50 years) less attractive, which may explain why few satellite centers become established in such young stands. The tendency for satellite centers to become established most frequently near the edges of large stand openings may be due to the birds' preference for this habitat (Thomas et al. 1979).

Although satellite centers may become more common in older lodgepole pine stands (over 50 years), their low frequency and low mistletoe intensities suggest that their effects on stand volume growth will be minimal if stands are harvested by age 100-120. Thus, potential mistletoe spread into clearcut areas is very low, and clearcutting to minimize damage due to dwarf mistletoes is still a sound silvicultural management practice in mature lodgepole pine (Hawksworth and Dooling 1984).

Acknowledgements

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A System That Monitors Blowing Snow in Forest Canopies

R. A. Schmidt and Robert L. Jairell[1]

Abstract--An electronic system that connects a desktop computer (PC) to tower-mounted arrays of snow particle counters provides a new approach to an old problem--why more snow accumulates in small openings than in the surrounding forest. Each photoelectric sensor generates a pulse for a particle passing through its light beam. These are counted by a microprocessor system that passes the sums to the PC. Preliminary measurements in both a clearing and the forest upwind show counts Increasing with height in the 15-m region centered near the mean canopy height (18 m).

Why do small forest clearings accumulate more snow than adjacent stands? This question has puzzled researchers since studies began at the Fraser Experimental Forest in Colorado. They developed two explanations: (1) snow trapped by the forest canopy (interception) evaporates in place, reducing snowpack on the forest floor, and (2) wind guides more snowfall (including interception) into the clearings (aerodynamic redistribution).

Interception was first favored as the likely explanation. Goodell (1959) measured evaporation of intercepted snow, and called for detailed analytical studies of the process (Goodell 1963). However, intensive measurements of snowpack on the Fool Creek watershed suggested that timber harvest did not increase total snow accumulation, compared to the East St. Louis control watershed (Hoover and Leaf 1967). This evidence supported the aerodynamic redistribution hypothesis, because reducing interception loss by timber harvest should increase total snow accumulation.

Researchers led by Charles Troendle have continued to measure the peak water equivalent of snow on Fool Creek and East St. Louis. With precision increased by a longer measuring period, it now appears that total snow accumulation on Fool Creek did increase about 9% after harvest. This increase approaches the 12% increase Hoover and Leaf (1967) said was expected, assuming all increased snowpack (and thus streamflow) resulted entirely from reduced interception loss (Troendle and King 1985).

Analytical experiments on the evaporation of blowing snow in the plains environment (Schmidt 1972, 1982; Tabler and Schmidt 1972; Tabler 1975), show how strongly surface area affects the process. The results support the likelihood that evaporation of intercepted snow explains the increased accumulation in clearings. Snow held on branches presents a huge extension of surface area exposed to moving air, compared to the snow surface in the clearing.

Intensive snowboard measurements reported by Wheeler (in press) for the 1985-86 winter, demonstrate that accumulation differences between clearing and forest (1) usually occur during storms, not between storms, and (2) are inversely related to wind speed during the storm. Both results, but especially the latter, argue against aerodynamic redistribution as the main cause of the difference.

The electronic system described here is a step toward the detailed studies of the distribution and evaporation of snowfall in forest canopies and clearings called for by Goodell in 1963. This paper presents a method of counting precipitating snow crystals, and shows example results from a cut block on the Fraser Experimental Forest.

Study Site

The cut block, 80m wide in a stand of mature spruce and lodgepole pine with an understory of subalpine fir, extends 100m down a north-facing slope (40%) draining into West St. Louis Creek, in the Fraser Experimental Forest (fig. 1). The block is near Short Creek, in the center of Section 8, T2S, R76W, at 2925m elevation (9600ft), 106°54' west longitude, 39°52'30" north latitude. Wind during storms is most often from the west to northwest at this site. Troendle designed the block and erected towers for these experiments, with the assistance of Manual H. Martinez, who also constructed the tower wiring harnesses and placed the cables between the

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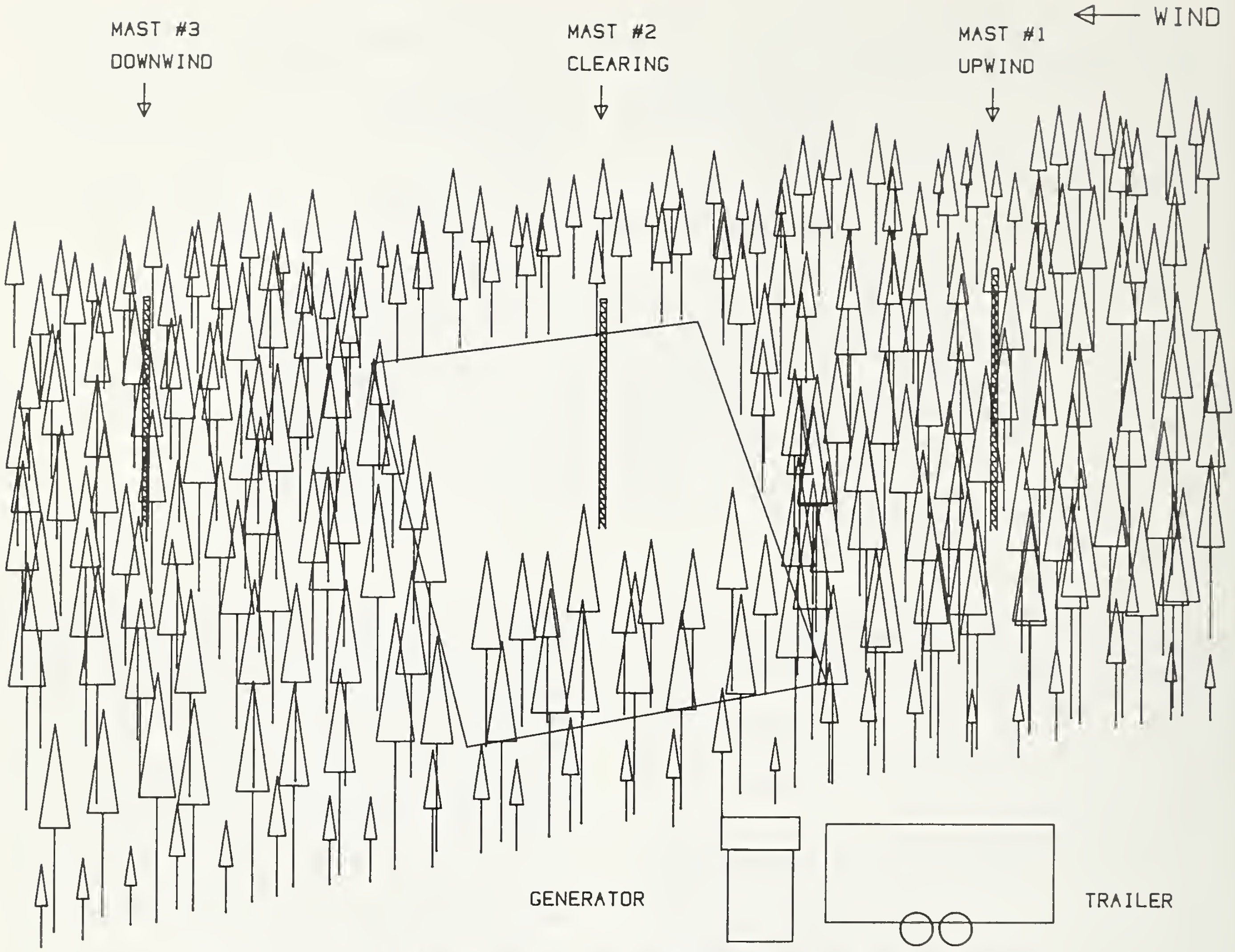

Figure 1.--The experimental site on West St. Louis Creek includes a cut block in a mixed stand of spruce, fir, and lodgepole pine. This clearing is 80m wide and extends 100m down a north-facing 40% slope. Towers are located (1) upwind, (2) center, and (3) downwind of the clearing, with 85m separating towers 1 and 2.

towers and the trailer. A 27m tower supports instruments in the center of the clearing, 40m east from the upwind edge. In the upwind forest, 85m from the clearing tower, a 34m tower extends about 16m above the average canopy height of 18m. A third tower in the forest downwind of the clearing was not used in initial experiments with this system. (All three towers carried triaxial anemometers at two levels as part of another study by David Miller.)

For the first tests, six sensors were uniformly spaced 3m (10ft) apart between 15 and 30m on the upwind mast during several storms. The lowest two sensors were below the average canopy height. All sensors were then deployed on the clearing tower, again at the same spacing, between 11 and 26m above the snow surface, during two storms. Finally, three sensors measured snowfall at the highest (#1), lowest (#6), and #4 position on both towers, allowing comparison of simultaneous counts in the forest and clearing.

Counting Snowflakes

The system (fig. 2) consists of the sensors mounted on towers, wiring harnesses on each tower to provide signal and power interconnections, cables from each tower to a small instrument trailer below the clearing, counting circuits that sum each sensor's signals, and the desk-top computer (PC). A propane-driven generator provides satisfactory electric power, since the system operates only during events when an observer is at the site.

The snow sensor, called a snow particle counter (SPC), is a device developed to measure the number and size of particles moving in blizzards (Schmidt 1977). Two phototransistors sense shadows cast by particles passing through a light beam (fig. 3), producing voltage pulses that are amplified at the sensor and sent to counting circuits. Pulse amplitude is related to the size of the particle's shadow. (For these initial

experiments, the system does not extract the information on particle size, however.)

The microprocessor system (fig. 2) passes counts from runs, of 1 to 10 min duration, to the computer for printing and storage on disk. Using an internal analog-to-digital converter, the computer also monitors wind speed and direction from an anemometer and vane mounted at 10m on the clearing tower.

To assure comparable sensitivity, each SPC is calibrated by spinning a wire through the beam and adjusting amplification for a standard output, measured as peak-to-peak pulse amplitude on an oscilloscope. This was accomplished before and after each day's experiment for the first few events, until experience showed such frequent calibrations were unnecessary. After that, calibrations were checked when some change was made in the setup, such as moving sensors between towers. (Miller equipped each tower with a safety rope and halyard system, which greatly facilitated calibration of the SPC's.)

Example Results

Although the objective of initial experiments was only to test the measurement technique, transfer from our laboratory to Dr. Troendle's study site proceeded so smoothly that he was able to test two hypotheses concerning the snow accumulation problem during March, 1987. Details will be reported elsewhere, but the hypotheses were: (1) There is no significant difference in particle counts between levels on a tower, and (2) There is no significant difference between average counts at each tower.

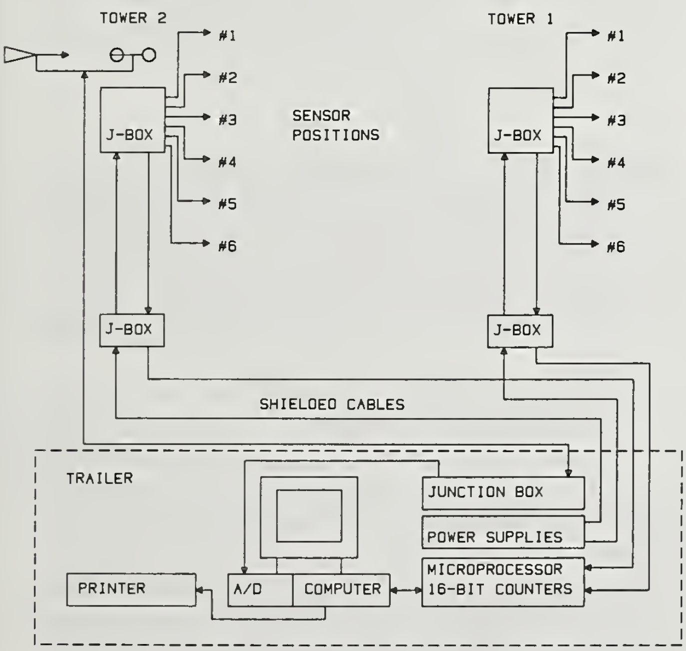

Figure 2.--Signals from each SPC on the towers are summed and transferred to the computer by a microprocessor system. An analog-to-digital converter in the computer measures voltages from wind speed and direction sensors at the 10-m height on tower 2, in the clearing.

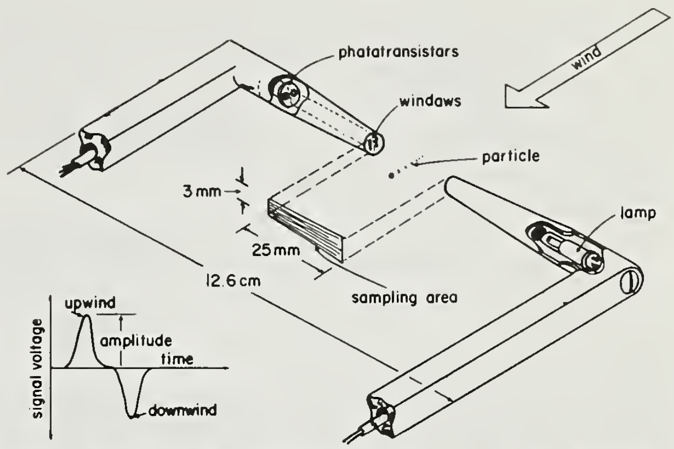

Figure 3.--The snow particle counter (SPC) senses the shadow of particles passing through the light beam, producing amplified voltage pulses. With two windows, estimates of particle speed are possible (from Schmidt 1977).

Figures 4a and 4b show typical examples of counts when all sensors were on one tower. Counts were normalized by the mean count of all sensors for each run, and heights were normalized by the midpoint and spacing of the sensor array. Figure 4c is a comparison of counts during a run with three sensors at each tower. We found no large differences in average counts between towers.

Although designed to measure the smaller particles and greater frequency of drifting in blizzards, the SPC's provided useful and apparently consistent measures of snowfall under light winds in a forest canopy.

Plans

If these preliminary results withstand tests for statistical significance, it appears that particle count usually increases with height both in the clearing and above the canopy (although the opposite gradient was occasionally observed). Average counts seem to be about the same at each tower, however. The next question is, "Are particle sizes similar?"-- that is, do these counts represent the same mass flux. We are adding electronics to determine size distributions for experiments during the 1987-88 winter.

To explain the decrease in count within the forest seems simple-- interception. Yet a similar gradient of particle numbers appears in the clearing measurements. Does this reflect an aerodynamic effect? Anemometers at each SPC location will help estimate particle trajectories in upcoming experiments with this system.

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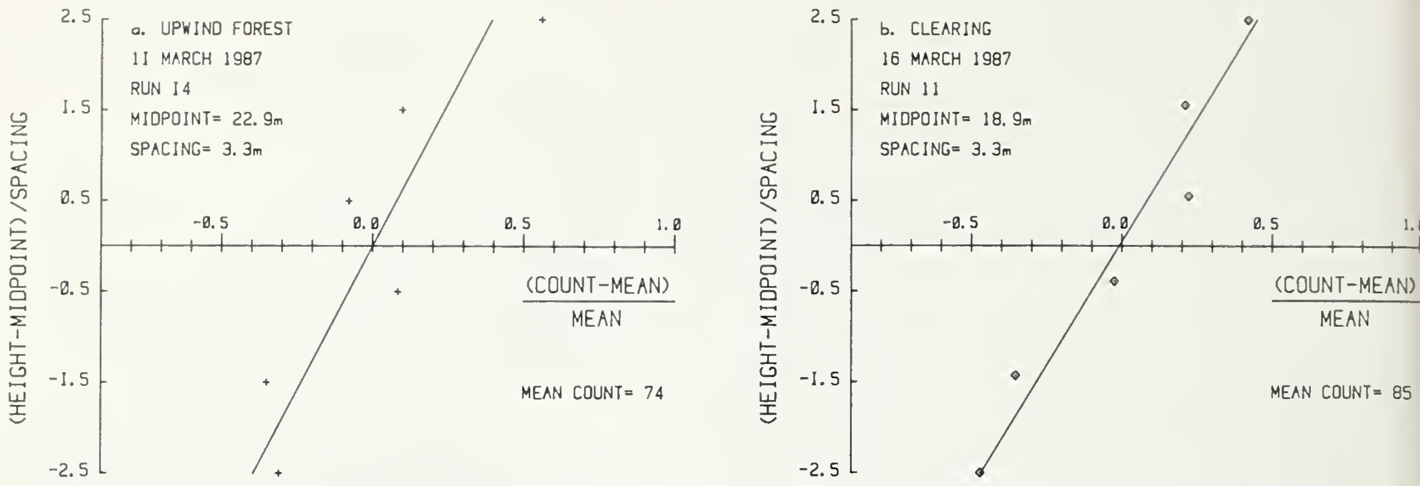

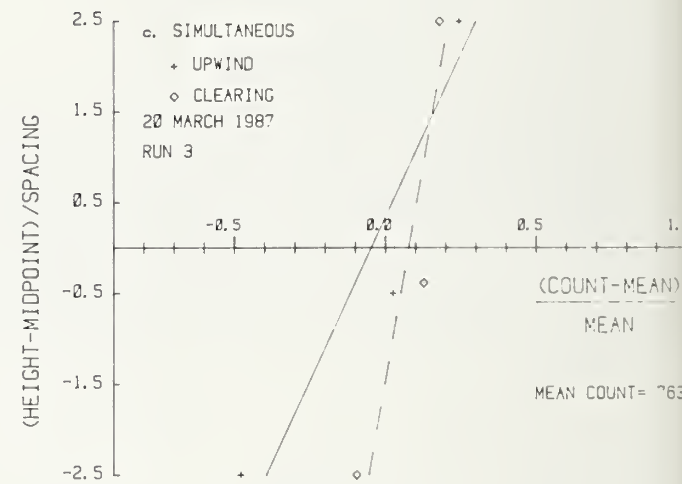

Figure 4.--Example plots of particle counts during 5-min runs with six sensors at (a) tower 1 (upwind) and (b) tower 2 (clearing). Three sensors at each tower gave the counts in (c). Both count and height are normalized by the respective means.

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Temperature Gradient Driven Vapor Transport in Snow

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Snow is a good insulator. The first snow layer of the season traps the heat that has been stored in the ground during the summer. This heat is slowly released to flow through the snow to the colder, upper surface of the snowpack. Part of the heat flow is carried by water molecules that move from the warmer to the colder grains. This temperature driven vapor flow causes extensive recrystallization in a process called temperature gradient metamorphism. Normal temperature fluctuations, and the snow's layered structure complicate the process. However, a simple system with a constant difference across a uniform snow layer can provide the information necessary for understanding the more complex system. Such a simple system is easily maintained in a cold laboratory.

Two different size scales are important in a quantitative understanding of the temperature gradient (TG) metamorphism caused by the temperature gradient across a snow layer. At the macroscopic level, the snow layer can be treated as a continuous infinite slab. The one dimensional temperature gradient causes a vapor pressure gradient across the slab and the vapor diffuses across the layer according to Fick's first law,

$$J = - D_{eff} \frac{\partial P}{\partial P} \qquad [1]$$

where J is the mass flow rate, D_{eff} is the effective diffusion coefficient of water vapor in snow, P is the water vapor pressure, and z is the vertical coordinate, perpendicular to the slab. Geometrical factors discussed below raise the possibility that D_{eff} is not equal to the diffusion coefficient of water vapor in air (D_w) but that

$$D_{eff} = K_s D_w \qquad [2]$$

where K_s depends on the microstructure of the snow.

It is easy to measure the temperature gradient through a snow slab, and to calculate the vapor pressure gradient from that. Normally, one would measure Deff by measuring the flow rate under a carefully controlled temperature gradient and thereby determine K_s. However, this is impossible in snow.

One serious problem in determining K_s is caused by the fact that the heat and mass flow are coupled. The temperature gradient provides the driving force for the mass flow which, because of the transfer of heat of fusion, affects the temperature gradient. This causes a curvature in the temperature gradient. The curvature also complicates the vapor pressure gradient (fig. 1). Further complications arise from the microscopic complexity of the ice network that makes up the snow. For example, it is not possible to determine independently the quantity of heat conducted through the ice so that the amount transferred by the mass flow could be determined.

To understand the microscopic complexity, it is necessary to understand that the microstructure of snow can include three types of grains. A "snow grain" can only be defined approximately as the obvious subunit at the microscopic level in snow (Sommerfeld and La Chapelle, 1970). While this definition is imprecise, the concept is nonetheless useful. Snow grains can be classified by their type of attachment in the snow microstructure as shown in figure 2 (Kry 1975). A grain with one bond is called a branch grain, with two bonds a chain grain, and with more than two bonds, a link grain. Other types of grains might be categorized (Gubler 1978), but this idealization is relatively simple and, as we will see, is sufficient for understanding TG metamorphism.

De Quervain (1973) shows a geometry (fig. 3) in which branch grains are important. Because the thermal conductivity of ice is about 100 times the thermal conductivity of air, the temperature gradient between branch grains and other grains will be increased. The increased gradient results in preferred growth sites such that some grains grow at the expense of others. Sommerfeld (1983) showed that about 50% of the grains disappeared during TG metamorphism. He pointed out that the disappearance of grains was a necessary consequence of the conservation of mass.

Yosida and colleagues (1955) pointed out that vapor transport in snow is different from that in other systems in that the solid and the liquid are the same substance. He termed this type of transport "hand to hand" because each grain receives water molecules "handed" from below and "hands" them to the grain above. Since it is not possible to distinguish among water molecules, the transport appears to proceed without obstruction by the solid phase. However, Yosida and colleagues (1955) modeled snow as a uniform distribution of grains without connection, ignoring some of the important microstructural features.

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Giddings and La Chapelle (1962) used a continuum model which also ignored important aspects of the microstructure. Like de Quervain (1958, 1973), they did not include conservation of mass and thus had an inaccurate estimate of mass flow.

Colbeck's (1983) calculations of vapor flow rate were based on a uniform distribution of ice spheres, and ignored the "hand to hand" character of the process and conservation of mass.

Gubler's (1985) model assumed that the "hand to hand" process was not important because the preferred growth sites were "shielded" from the grains above. Gubler (1985) did not present any data to support this assumption. "Shielding" is not evident in the movie sequences of TG metamorphism filmed by Kuroiwa (1975).

The first model to include all the important features of TG metamorphism mentioned above was that of Christon et al. (in press). They used a finite element model that idealized the snow as a two dimensional grid with various orientations of branch grains. Their model conserved mass and solved the coupled heat and mass flow problem. Depending on the branch grain geometry, Christon et al. calculated flow rate enhancement factors (K_s) up to 2.5.

Measurements of K_s or D_{eff} are necessary to test the above model. D_{eff} can be measured using isotopic fractionation of the naturally occurring stable isotopic species in the snow, HDO and $H_2{}^{18}O$. Primarily because of their larger molecular weights, these species have lower vapor pressures and lower diffusion coefficients than normal H_2O. If the snow can be considered as a continuum, the following equation is applicable,

$$\frac{d\left[m_{iso} / m_{H_2O}\right]}{dt} = \left[\frac{1}{m_{H_2O}}\right] \cdot \left[\frac{dm_{iso}}{dt} - \frac{m_{iso}}{m_{H_2O}} \frac{dm_{H_2O}}{dt}\right] . \qquad [3]$$

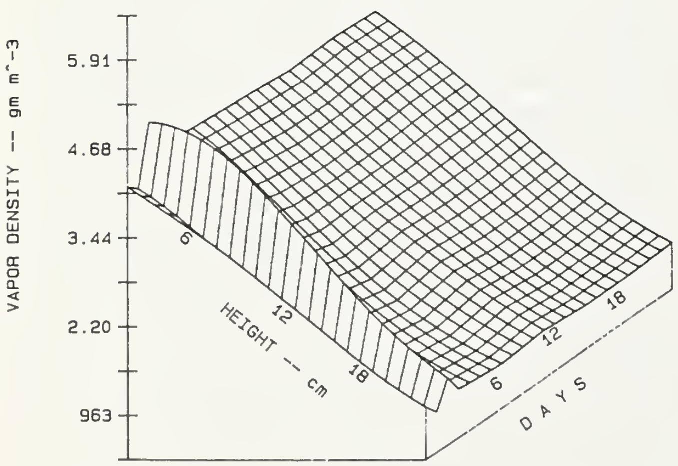

Figure 1.--Vapor pressure gradient. The curvature with height is caused by the coupled heat and mass transport.

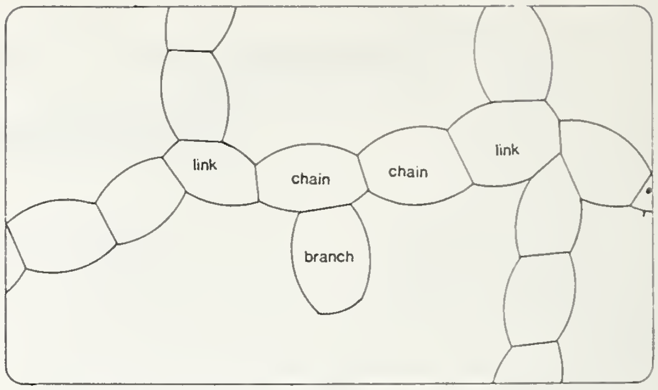

Figure 2.--Grain types in snow after Kry (1975).

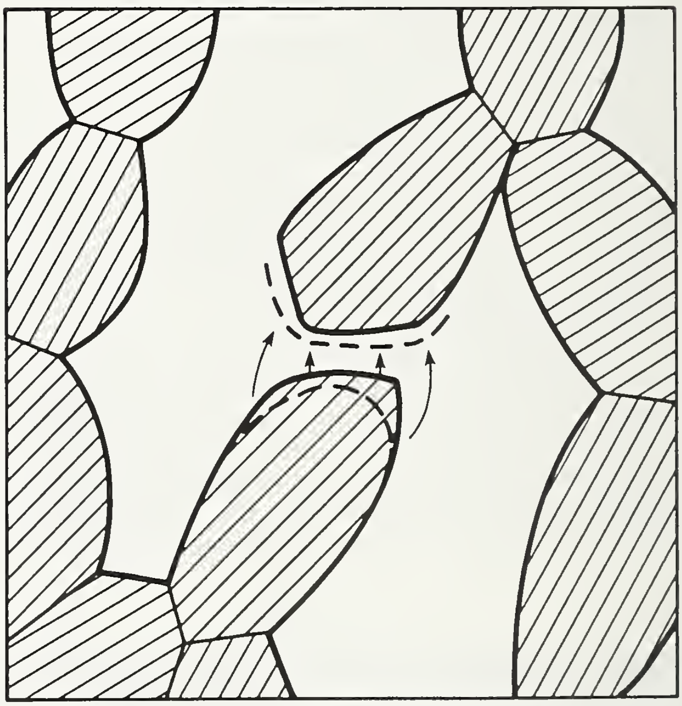

Figure 3.--Branch grain growth and decay after de Quervain (1973).

m is the mass concentration and the subscript refers to either the isotopic species or normal H_2O. Fick's second law for one dimensional flow is,

$$\frac{dm}{dt} = D_{eff} \frac{d^2m}{dz^2} . \qquad [4]$$

Thus, if there is no curvature in the mass concentration gradient, the change in the isotopic ratio is zero. The curvature is small in the center of a snow layer (fig. 1) when the temperature differential is held constant. However, there may be a considerable curvature near the upper and lower boundaries, particularly where the boundaries are impermeable. Then the vapor pressure changes from zero to that of ice in a short space.

This raises the problem of the microstructure. If snow strictly followed Yosida's hand to hand concept, a very large,

but finite change in the second derivative would occur only in the first layer of ice grains next to the boundaries. This effect might be observable with very careful work. Essentially, Yosida's model assigns a communication distance of one grain size to the transport of water vapor. The second possibility is that the average communication distance between grains is larger than one grain diameter.

Figure 4 shows schematically the isotopic ratios that would be expected after a period of time under the two models. Figure 5 shows the results of a series of measurements on snow samples held under a constant temperature difference for about one month. The first curve shows the transient effect from the initial high gradient at the boundaries that occurred when the temperature at the boundaries was first established. The change in isotopic ratio shows that the lowest layer lost mass to layers above it, and that the top layer lost mass to the plate that formed the upper boundary. After one month, the lower layers continued to lose mass while the upper layers gained mass. Furthermore, the knee in the lower part of the curve continued to move up. The experimental curves are most like figure 4C, which represents a communication distance of more than one grain diameter. The grain diameter was of the order of 1 mm while figure 5 indicates that the mean communication distance is of the order of 10 mm, roughly 10 grains.

As equation [3] implies, the change of the isotopic ratios in a layer is directly related to the mass change of the layer. If mass is transported out of the layer, it loses more normal H_2O and the isotopic ratio increases. The opposite is true if it gains mass. Moser and Stichler (1980) present an experimental determination of the relationship between mass change and the change in the isotopic ratio. With this relationship and the measurements shown in figure 5, it is possible to calculate K_S. Both the HDO and the $H_2{}^{18}O$ results give

$$K_S = 2.3 \pm 0.2.$$

This result agrees with the maximum value calculated using the computer model of Christon et al. (in press).

These results are preliminary because (1) the accuracy of the results of Moser and Stichler (1980) has not been verified, and (2) the relationship between K_S and the microstructure

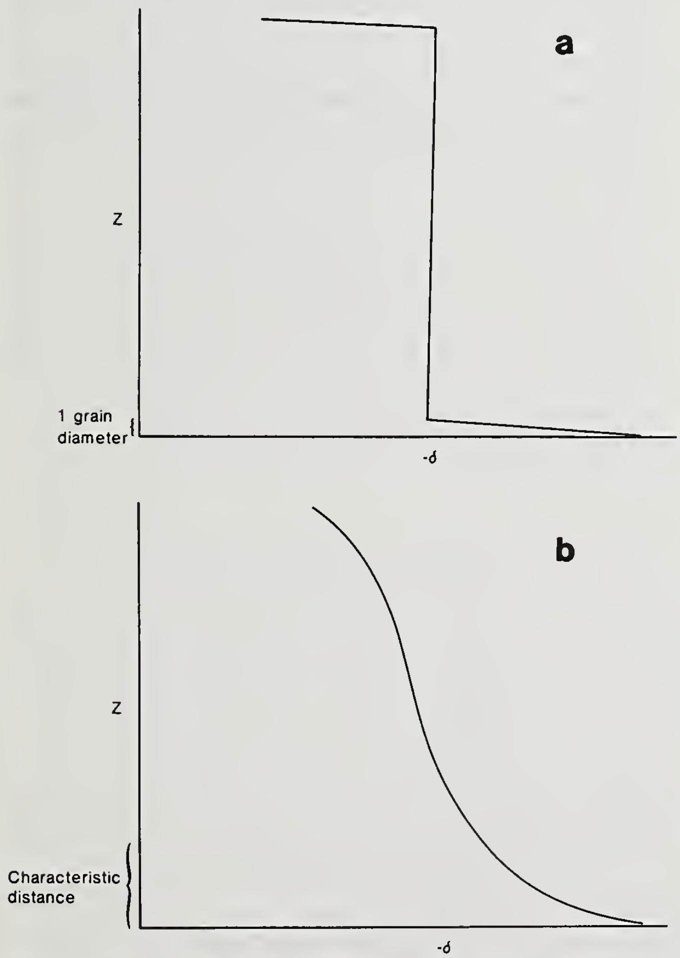

Figure 4.--Idealized profiles of isotopic ratios after TG metamorphism. (a) single crystal, hand to hand transport, and (b) hand to hand transport with a communication distance.

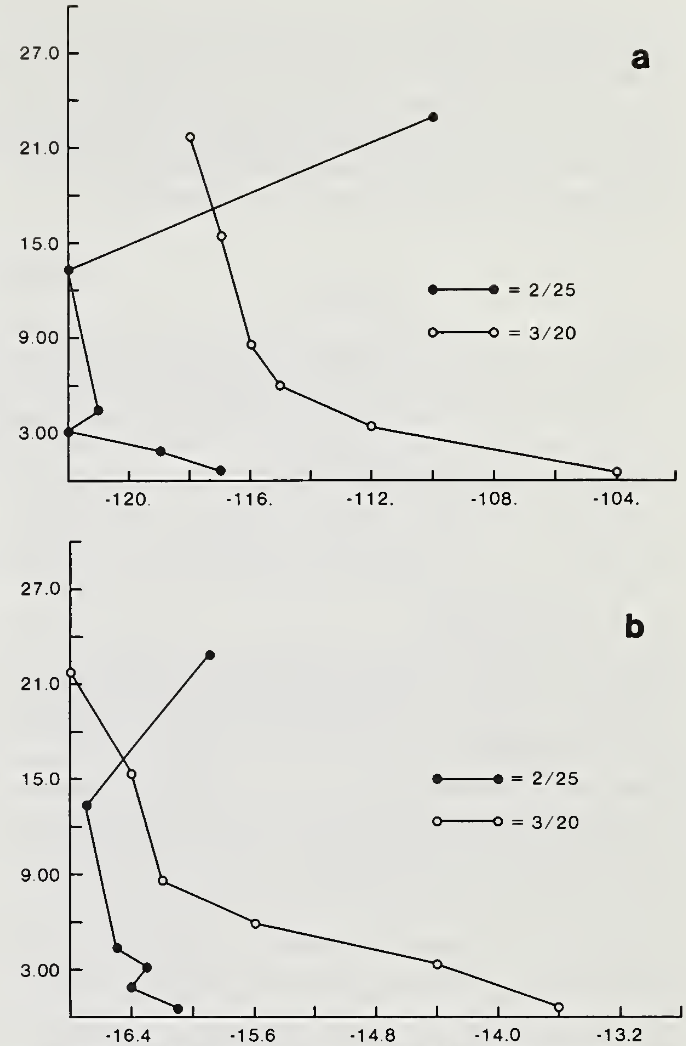

Figure 5.--Measured profiles of isotopic ratios. (a) HDO, and (b) $H_2{}^{18}O$.

cannot be determined from this single experiment. However, the results show that the communication distance for vapor transport in snow is significantly larger than one grain diameter. Snow can therefore be treated as a continuum, K_S can be determined by measuring the changes in isotopic ratios and, in general, the mass change in a snow layer due to vapor transport can be determined from changes in the isotope ratios.

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Ecosystem Studies in the Subalpine Coniferous Forests of Wyoming

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Abstract--An overview is presented on recent ecosystem studies in the Medicine Bow National Forest and Yellowstone National Park. Most of the research has focused on lodgepole pine forests. Hydrology, leaf area development, decomposition, nutrient dynamics, soil chemistry, landscape ecology, and the effects of tree harvest, fire, and mountain pine beetles have been emphasized.

The subalpine elevations of Wyoming mountain ranges are characterized by a mosaic of meadows, lakes, and forests dominated by various mixtures of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and aspen (*Populus tremuloides* Michx.). As in other parts of the Rocky Mountains, vegetation patterns are determined by environmental factors associated with elevation, topographic position, soil characteristics, and the history of disturbances including fire, logging, and outbreaks of the mountain pine beetle (*Dendroctonous ponderosae* Hopk.). On the warmer and drier sites lodgepole pine appears to form a stable community that persists until fuel accumulation makes the next fire inevitable (Romme and Knight 1981, Despain 1983). Elsewhere spruce and fir are the climax species, sometimes developing in the understory of pioneer lodgepole pine or aspen forests but in other cases invading directly following a burn or some other disturbance (Stahelin 1943, Romme and Knight 1981).

For many years research on the subalpine forests of Wyoming was focused on species composition, classification, and succession. Such studies are essential for providing the understanding required for sound resource management, but many questions pertaining to nutrient cycling and water flows were not being addressed. Of course, research at the nearby Fraser Experimental Forest was providing good information on forest hydrology, but more remained to be done. Recognizing the importance of such research for management, my colleagues and I began to study the subalpine forests of Wyoming from an ecosystem perspective. In this paper I will provide an overview of some of our results thus far.

Most of our research thus far has focused on forests dominated by lodgepole pine and has been done at the stand level rather than at the scale of the watershed. Originally we had hoped to find a watershed in Wyoming that could be studied in the manner of the Fraser or Hubbard Brook watersheds, but during the search we concluded that our watersheds were so heterogeneous (in terms of vegetation, soils, and geologic substrate) that it would be difficult to evaluate biotic effects on water and nutrient fluxes -- one of our primary interests. Instead we selected homogeneous stands of a few hectares as our ecosystems. Such stands had the advantage of being closer to the scale of an actual timber sale than whole watersheds, and we hoped that they would provide the opportunity to examine more precisely the effects of vegetation structure on ecosystem processes. Studying stands instead of watersheds has its problems (Knight et al. 1985), but we felt they could be resolved in the relatively simple lodgepole pine forest. Most of the research has been done in the Medicine Bow National Forest, 50 km west of Laramie, but several studies were conducted in Yellowstone and Grand Teton National Parks as well.

Many individuals have helped in the development of our research, including colleagues at neighboring universities and with federal agencies, but the following individuals deserve special recognition: James F. Reynolds, Ned Fetcher, William H. Romme, Steven W. Running, Timothy J. Fahey, John A. Pearson, Joseph B. Yavitt, and Howard E. Haemmerle. These graduate students, listed in order of degree completion, worked long hours for little reward other than a chance to make a contribution to forest science. To a very large extent, it is their results that are highlighted in this overview. I am also especially grateful for the cooperation extended to us by the staff of the Medicine Bow National Forest. Our research has been funded by the National Science Foundation, Wyoming Water Research Center, University of Wyoming - National Park Service Research Center, Department of Interior (Office of Water Research and Technology), and the Department of Agriculture (U. S. Forest Service, Rocky Mountain Forest and Range Experiment Station).

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Stand Hydrology

The streams draining Wyoming watersheds are important as sources of water for the semiarid basins below, as habitat for a popular sport fishery, and as sources of nutrients and sediments in downstream reservoirs. Everyone recognizes that streamflow is affected by watershed vegetation, but little was known about the hydrology of lodgepole pine forest at the scale of single stands. Reynolds and Knight (1973) calculated the importance of forest floor interception following summer rains, concluding that in most years winter snowfall is the only source of water adequate to cause water outflow beyond the rooting zone. Normally, only one pulse of outflow occurs each year. Moreover, the primary source of water for the lodgepole pine is from snowmelt, as most rains are completely intercepted by the canopy and forest floor.

The amount of spring outflow from a stand is dependent on the storage capacity for snowmelt water created by evapotranspiration (ET) during the previous year. Transpiration is known to be a substantial part of ET, but few data were available for stands of Rocky Mountain coniferous forest. Fetcher (1976) found that lodgepole pine stomatal resistance could be an important factor reducing transpiration towards the end of the growing season and that the degree of control was greater on drier sites. This information added to a growing body of information on the water relations of lodgepole pine (Swanson 1967, Owston, et al. 1972, Johnston 1975). With the assistance of better instruments for measuring transpiration in the field, Fahey (1979) and Running (1980a, 1980b) were able to accomplish a more detailed analysis of lodgepole pine stomatal behavior in relation to environmental conditions. Kaufmann (1984a, 1984b) conducted similar research on lodgepole pine, subalpine fir, and Engelmann spruce in Colorado.

Understanding stomatal physiology is important for hydrologic studies, but extrapolating to the whole tree or forest is difficult. Our initial attempt to resolve this problem for lodgepole pine was with the use of whole-tree potometers (Knight, et al. 1981). Entire 100-yr-old trees, up to 26 cm d.b.h., were cut and suspended in reservoirs of water for periods of several days. Careful monitoring suggested that the rate of water loss from the reservoir was a reasonable estimate of tree transpiration. Tree diameter and maximum observed 24-hour uptake were highly correlated, with the largest trees transpiring 40-44 L on clear days in early summer. Maximum observed hourly uptake for the larger trees was 2.5 to 3.5 L, with total nighttime uptake being about 12% of 24-hour uptake. On overcast days potometer uptake was reduced by 30-34%. Transpiration data for trees of different sizes were used to estimate a total clear-day transpiration from the forest of 3.3 mm. Interestingly, a very dense "dog-hair" stand, with 14,000 trees/ha, had about the same leaf area index (7) and transpiration rate as an adjacent more open stand with 2,000 trees/ha and a much higher basal area/ha.

Our most recent analysis of lodgepole pine forest hydrology involved more detailed measurements and a stand-level computer simulation model (Knight et al. 1985). Eight contrasting stands were compared over a 3-year period. Estimates of actual ET for the period from early spring to late fall ranged from 21 to 53 cm, which was 33-95% (x = 73%) of total annual precipitation. For all stands and years, transpiration accounted for 50-61% of ET, and 9-44% of the transpiration occurred during the spring drainage period while snow still covered the ground (vernal transpiration, VT). Estimated VT and outflow varied considerably among the stands (fig. 1), with VT accounting for 4-20% of the snow water. We estimated that outflow beyond the rooting zone occurred only during the snow melt period and accounted for 0-80% of the snow water.

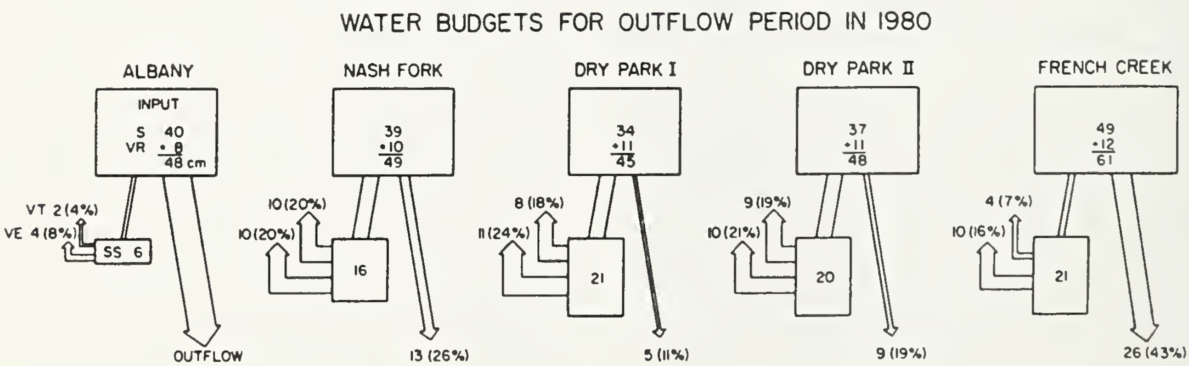

Figure 1.--Diagrams depicting the water budget of five contrasting stands of lodgepole pine forest during the 1980 outflow period (from the initiation of snow melt until the end of drainage). Units are cm-H_2O. See figure 2 for a generalized annual budget. The amount added to the value for the maximum snow water equivalent (S) is vernal rainfall (VR), i.e., rainfall that occurred during the snow melt period. The smaller boxes represent soil storage (SS) and are full at the end of the outflow period. Percentages in parentheses indicate the proportion of S + VR flowing via outflow, vernal transpiration (VT), and vernal interception (VE) during the outflow period (as estimated with a computer simulation model). From Knight et al. (1985); reprinted with permission of the Ecological Society of America.

Outflow could be reduced to zero under conditions of high VT, high soil storage capacity, high LAI, relatively slow snowmelt, and average or below snow water equivalent. The hydrology of deciduous aspen forests should be considerably different because they lack the potential for VT, but we have not yet studied this kind of vegetation in detail. Figure 2 contrasts the hydrology of a typical stand of Wyoming lodgepole pine to a stand of Douglas fir in Oregon.

In sum, our results are helping to quantify the generally accepted concept that stands differing in structure and environmental conditions experience different rates of water outflow at different times during the snow melt season, contributing differentially to stream hydrograph shape.

Forest Leaf Area

Leaf area, whether evergreen or deciduous, is an important determinant of transpiration rate as well as photosynthesis and aerosol impaction, but until recently little information has been available on this important forest parameter. Usually leaf area is expressed as leaf area index (LAI, m^2 leaf surface area/m^2 ground surface area). Deciduous forest LAI is often calculated for a single leaf surface while all surfaces are commonly included for the LAI of coniferous forests.

LAI is a stand feature that varies with habitat type and is, of course, affected by silvicultural practices. Utilizing our computer simulation model, which includes LAI as a key variable, we observed that increases in water outflow following any kind of disturbance is proportional to the decrease in leaf area (Knight et al. 1985). Removal of leaf area appears to be more important than reductions in tree density or basal area (Knight et al. 1981).

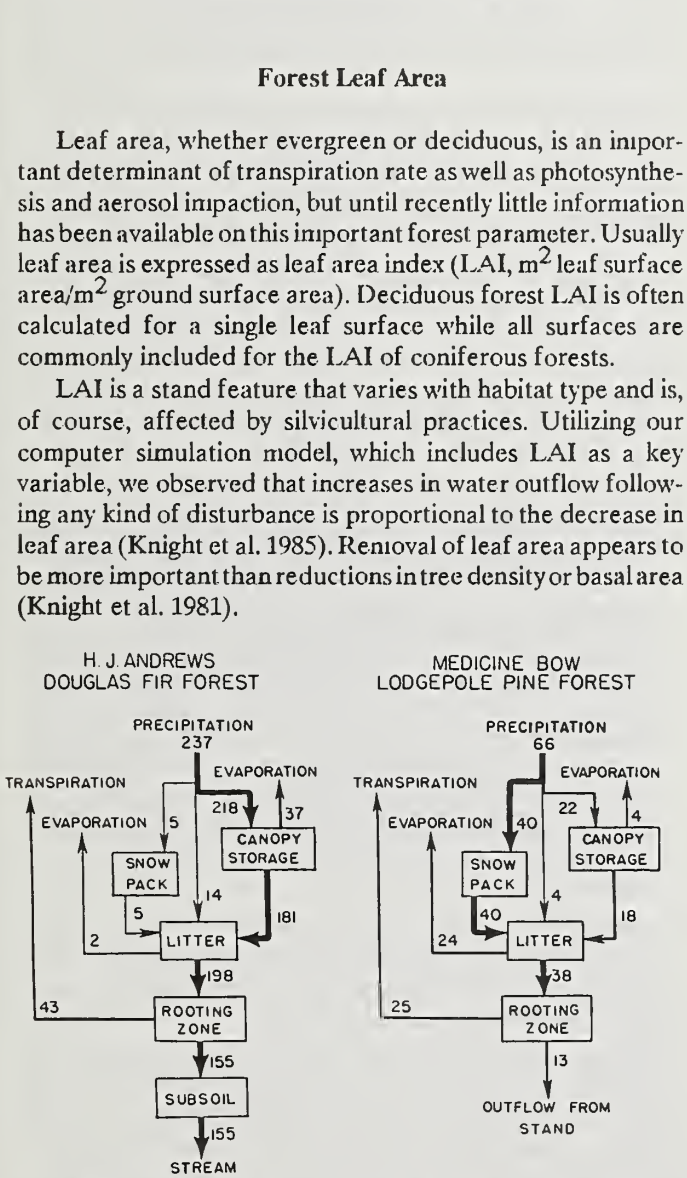

Figure 2.--Generalized annual hydrologic budgets for the H. J. Andrews Douglas fir forest in Oregon and a typical stand of lodgepole pine forest in the Medicine Bow Mountains. Numbers are cm-H_2O per year. The figure for Douglas fir is redrawn from Sollins, et al. (1980), and is used with permission of the Ecological Society of America.

These observations led to a study designed to determine how LAI changes with site quality and forest age (Haemmerle et al., submitted). Forty-three stands in the Medicine Bow Mountains were divided into two series, one in which lodgepole pine appeared to be the long-term dominant and another where subalpine fir was common. A maximum LAI of 16 was calculated for a stand from the pine series, while 39 was the maximum LAI for the fir series. Maximum leaf area in the pine and fir series is reached in 125-200+ and 200-300+ years, respectively, with more time required as site quality declines. Differences in maximum leaf area and the timing of this maximum probably are caused by tree establishment patterns, physiological differences among species, and site water balance. The relationship of LAI to important ecosystem processes and the fact that LAI is now being estimated more easily (Pearson et al. 1984, Haemmerle et al., submitted), even from satellites (Running 1986), suggests that it can and should be used more frequently in forest management decisions.

Nutrient Conservation and Outflow

Water passing through the soil profile, beyond the root zone, carries dissolved nutrients which are losses to the terrestrial ecosystem but inputs to ground and surface water systems. Considering that a large proportion of litter decomposition occurs during the winter under snow (Fahey 1983), and that the only pulse of water adequate for leaching occurs in the early spring before vigorous tree growth, we wondered if each year there is a "spring flush" of nutrients beyond the rooting zone that tends to maintain the soils in a nutrient-deficient state. Nutrient outflow/atmospheric input ratios were estimated, with the results being consistently < 1.0 for N; consistently > 1.0 for Ca, Na, and Mg; and ranging from 0.3 to 2.0 for P and 0.2 to 3.3 for K. These results suggest that N usually is accumulating in lodgepole pine forest ecosystems, even during years of heavy snowpack and and large volumes of outflow, probably due to microbial or vascular plant uptake; and that P and K may accumulate on some sites. Weathering, another input for elements other than N, could not be estimated for our analysis and, therefore, the ratios for these elements are difficult to interpret.

Simple estimates of nutrient inputs and outputs are useful for ecosystem studies, but they ignore the processes involved. To improve our understanding, several studies were initiated on litter decomposition, nutrient retention, and other factors affecting soil water chemistry. The nutrient dynamics of aboveground detritus were studied by Fahey (1983), who found that decaying leaves and wood actually increase in N, P, and Ca during some stages of decomposition. For example, nitrogen content of decaying boles doubled between 30 and 55 years following tree death before beginning a slow decline after the C/N ratio of the wood drops to a critical level (Fahey and Knight 1986). This and other research suggests that N is one of several limiting factors for the lodgepole pine ecosystem, whether for the microbes or vascular plants, and that

decaying logs may be an important source of N for sustained site productivity. Dead wood resulting from the last disturbance, usually a fire in the case of our stands, was a major nutrient storage compartment, sometimes exceeding other forest floor components by several-fold in 80-100 yr old stands. Silvicultural practices that lead to significant reductions in the amount of woody detritus may be detrimental to long-term site productivity.

Ecologists and managers commonly focus on aboveground biomass, but Pearson et al. (1983) estimated the amount of root biomass as well in Wyoming lodgepole pine forest. They found that the average proportions of biomass in boles, branches, foliage, woody roots, and fine roots were 61, 7, 6, 20, and 6%, respectively, with root/shoot ratios ranging from 0.27 to 0.50. The highest ratios were in the more dense stands. Interestingly, the proportion of biomass in fine roots was about equal to the proportion in leaves. Ninety percent of the root biomass was within 40 cm of the surface in lodgepole pine forests, though tap roots were observed down to a depth of 2 m or more. Whereas Fahey (1983) studied detrital decomposition above ground, Yavitt and Fahey (1982) estimated rates of root decomposition. Despite being in closer proximity to soil moisture and soil microbes, woody roots appeared to decompose no more rapidly than aboveground boles of comparable size. Both may last a century or more. Complete mineralization of leaves requires 12-22 years, depending on site conditions (Fahey 1983).

As decomposition occurs, the soil solution is enriched in a variety of ions that could be leached beyond the rooting zone. For a time we thought that N was retained within the forest floor, due to the extremely low concentrations of NH_4^+ and NO_3^- in forest floor leachate, but subsequent studies revealed that the major transfer of N from detritus to mineral soils occurred in soluble organic compounds (Yavitt and Fahey 1985, Fahey et al. 1985, Yavitt and Fahey 1986). However, despite relatively high N fluxes to the mineral soil in organic compounds, little N of any kind could be detected in water samples collected near the bottom of the rooting zone. Observing that finer textured soils had lower N concentrations than more coarse soils, Fahey and Yavitt hypothesized that adsorption onto colloids was an important abiotic mechanism for N immobilization.

Annual N inputs from fixation and precipitation appear to be very low in lodgepole pine forests (fig. 3), as are decomposition rates, and consequently N could be an important limiting factor along with the short, cool, sometimes dry growing season (Fahey and Knight 1986). Fahey et al. (1985) found that about 90% of the N pool was in the soil organic matter, with 6% and 4% in aboveground detritus and living biomass, respectively. They hypothesized that some of the N available for microbial growth in the detritus was translocated to the forest floor from the mineral soil by fungal mycelia, and that a portion of the N required for tree growth was obtained by translocation from senescing leaves to twigs (as reported for other conifers, Gosz 1980). Of course, the slowly decomposing forest floor and soil organic matter are important sources as well. David Coleman and his associates, from the University of Georgia and Colorado State University, are studying the interspecific microbial interactions affecting decomposition in one of our Medicine Bow study areas.

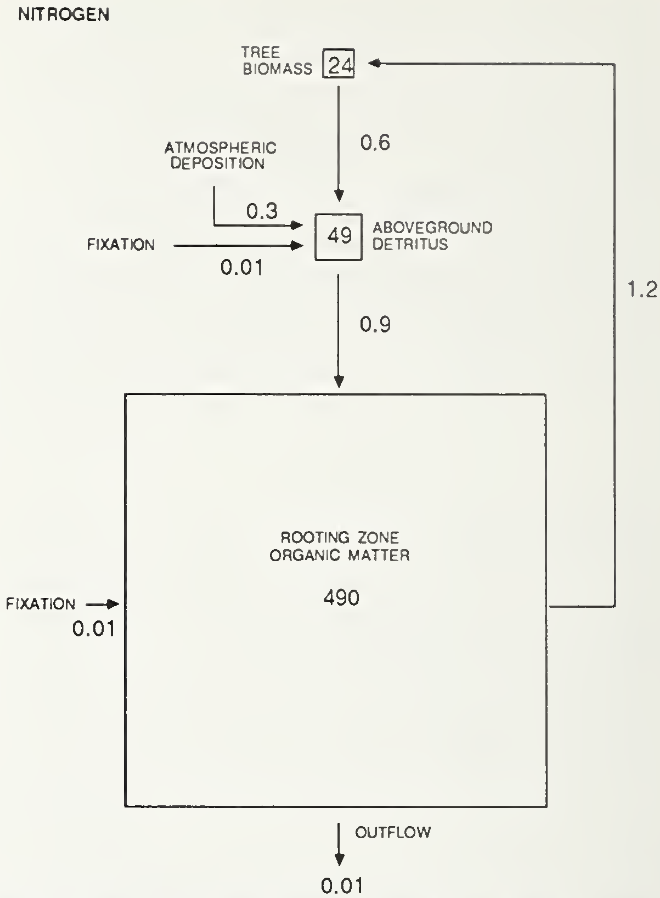

Figure 3.--Generalized annual nitrogen budget for a typical 100-yr-old stand of lodgepole pine forest in the Medicine Bow Mountains, drawn from data presented in Fahey et al. (1985). Numbers in boxes and by arrows are g/m^2 and g/m^2/yr, respectively. Much of the N in the rooting zone compartment is in organic matter that apparently is not readily decomposable, as the mean tissue N concentration of the foliage is low (0.7%) compared to other coniferous species. Note (1) that N inputs to the ecosystem are larger than N losses, suggesting that N is accumulating, probably due to being a limiting factor for the biota; and (2) that the tree uptake estimate is larger than the sum of the input estimates to the rooting zone, which suggests that the soil N pool is gradually being depleted in this aggrading forest. Replenishment of the soil N pool may occur as the forest ages further (Fahey and Knight 1986).

Other chemical fluxes have been studied, with the observation that the slightly acidic rainfall (mean pH = 4.6) is commonly neutralized to pH 5.2, probably by basic, microscopic aerosols (dry deposition) from upwind deserts (Fahey and Knight 1986). The neutralizing capacity of forest soils in the Medicine Bow Mountains is substantial due to the accumulation of such aerosols, an observation relevant to concerns being expressed about acid precipitation (Reiners et al., in preparation). Potential nutrient loss via leaching is accelerated by acidic soil water (Fahey et al. 1985), whether natural

or anthropogenic, but biotic sources of hydrogen ions appear to be more important than precipitation at the present time (Fahey and Knight 1986).

Effects of Disturbances and Succession

A widespread technique for studying ecosystems is to monitor changes in energy, water, and nutrient fluxes following disturbances to the biota. Sometimes natural disturbances such as fires or insect outbreaks can be used, but more controlled "treatment" perturbations and computer simulation "experiments" are other options. All three have been used in our research. Most have been done at the scale of a single stand covering several hectares, but others have focused on landscapes.

Our initial studies at the stand level involved simulation of a clearcut using the hydrologic model H2OTRANS (Running 1984, Knight et al. 1985). Computer simulations suggested that the increase in water outflow is, to a large extent, dependent on the amount of leaf area removed. Of course, timber harvesting is a standard tool for increasing streamflow.

Another approach was tree thinning. A 20 x 40 m plot in our Fox Park stand was thinned by tree girdling and another comparable plot was clearcut. A control stand was located within 40 m on the same soil type. The experiment provided an opportunity to examine the effects of removing two levels of leaf area and killing different numbers of trees. The thinning treatment was designed to duplicate, to the extent possible, the effects of a mountain pine beetle outbreak and included painting the exposed sapwood with spores of blue stain fungi -- the type of fungi that are also introduced by the beetles and which are believed to account for the rapid demise of the shoots (we observed that trees that are only girdled may live for 5 years or more). The clearcut and thinning treatments were applied in 1982, with the hypothesis that increases in water and nutrient outflow would be proportional to the amount of leaf area removed (clearcut > thinned > control).

The results for nutrient outflow were not what we anticipated (Knight et al, in preparation). Killing 60% of the trees by girdling, mostly the larger trees (as often occurs following a bark beetle infestation), had very little if any effect on the outflow of N, K, and Ca. In contrast, killing all of the trees via clearcutting increased N outflow by 40 times, K outflow by 3 times, and Ca outflow by 3 times. A similar pattern was observed for the concentrations of nitrate and total nitrogen in soil solutions. Hardly any concentration differences were observed when comparing the control and girdled stands, but nitrate concentrations were commonly > 100 times higher in the clearcut stand.

These results are interesting from at least two perspectives. First, we wondered if the high C/N ratios of the forest floor might negate the importance of N uptake by trees for limiting N outflow beyond the rooting zone. This proved not to be the case, as an abundance of leachable nitrate was observed in the clearcut stand. Apparently nitrification bacteria were able to produce more nitrate when competition for N by the trees was eliminated. While somewhat warmer soil surface temperatures would have existed in the clearcut stand, it seems doubtful that this difference alone could produce the great differences observed.

Secondly, the results of our experiment imply that the surviving trees in a thinned stand are able to absorb the nutrients formerly being used by the "dead trees." Our first inclination was to think that the roots of adjacent trees are so intermingled that as the roots of one tree die, the roots of nearby trees grow to fill any root gaps that are created. This may be the case, but other explanations are possible. For example, the root systems of adjacent trees are commonly grafted in pine forests (Graham and Bormann 1966). Is it possible that the root system of the surviving tree could somehow sustain through grafts, or mycorrhizal connections, the root system of the girdled tree? Do root systems become dysfunctional at the same time as the shoot dies? Are root gaps created at the same time as canopy gaps? Research on these questions is currently underway in one of our lodgepole pine stands. The results should clarify root growth dynamics following disturbances and the importance of root growth for regulating nutrient outflow.

Ecosystem development or change following disturbance is a topic of widespread interest among ecologists. The comparison of stands of different ages but on similar sites is a common approach for addressing this topic, but Pearson et al. (in press) attempted to use the tree ring record in the living and dead trees to examine biomass and nutrient accumulation during the history of the relatively simple lodgepole pine forest in our area. Changes in dead wood, forest floor, and live tree biomass (including roots) were estimated separately. Maximum total biomass accumulation rates of 2.5-3.2 metric tons/ha/yr were reached 40-60 years after fire in even-aged stands, but an uneven-aged stand developing on a former meadow did not achieve a maximum accumulation rate (1.5 tons/ha/yr) until after 80 years. Biomass increment occurred primarily in the living vegetation compartment throughout stand development, except for brief episodes of increment in the dead wood compartment associated with the mortality of large trees. Maximum forest floor biomass increment generally was about 25% as high as maximum living biomass increment. It is difficult to say when biomass accumulation rates will approach zero, i.e., when net primary productivity is balanced by heterotrophic respiration, and indeed the stand may burn before this happens. With sufficient time fuels develop to the point where fires become inevitable, whether the ignition source is lightning or humans.

With regard to nutrient accumulation, Pearson et al. (in press) suggest that the forest floor is the major biomass compartment accounting for the immobilization of N, P, Ca, and Mg, at least during the first 40-80 years of stand development. Living biomass appears to be next most important, especially after 60-80 years, and accounted for most K accumulation throughout stand development. The importance of dead wood is suggested as well, especially while the stand is

about 20-80 years old and when dead wood from the previous forest is still an active site for nutrient immobilization. Nutrient increment rates remained positive even in the oldest stand (about 200 years old).

Mountain Pine Beetle Ecology

As noted, outbreaks of mountain pine beetle are a natural disturbance in many western coniferous forests. A common notion is that older stands become more susceptible to the bark beetles, which create canopy gaps that release the growth of smaller suppressed trees, thereby maintaining a higher level of primary productivity than would occur otherwise. The interaction brings to mind cybernetic systems with feedbacks that control certain processes, in this case photosynthesis. Romme et al. (1986) examined this question in Yellowstone and Grand Teton National Parks, observing that indeed annual wood production per hectare usually returned to pre-outbreak levels or exceeded them within 10-15 years. However, their estimates of annual wood production over the last 70-80 years indicated that the beetle outbreak introduced more variation in productivity than would have existed in their absence. They concluded that the mountain pine beetle do not function as cybernetic regulators, at least in the strict sense. Nevertheless, because of the rapid recovery of annual wood production, they suggested that the effects of the beetles could be considered generally benign or even beneficial in some situations (e.g., increased understory growth may favor certain animals).

Could outbreaks of the mountain pine beetle affect the probability of crown fires? In another study in Yellowstone National Park, Romme et al. (in preparation) concluded that, while flammability may increase during the first year or two after an infestation because of dead leaves still on the trees, the risk of destructive fire during years 2-20 may be lower because (1) the leaves and many twigs fall off, reducing fuel continuity, and (2) the proportionate increase in forest floor fine fuels is small by the time the forest is old enough to be susceptible to a beetle outbreak. Accelerated growth in understory trees may increase fuel continuity and fire risk after 20 years.

Other studies have been done on forest fire ecology in Wyoming (Loope and Gruell 1973, Despain and Sellers 1977, Bartos and Mueggler 1979, Romme and Knight 1981, Romme 1982, Despain 1983, 1985; Knight 1987; Stottlemeyer 1987). Some of these studies focus more on community succession than on energy-, water-, and nutrient-related processes, but all aspects of disturbance ecology are relevant to understanding ecosystems.

Landscape Ecology

In recent years ecologists have become more conscious of the scale at which their research is being done. Some focus on leaves or other appendages; others focus on whole organisms, and still others on communities, i.e., rather arbitrarily defined assemblages of organisms. As usually addressed, the ecosystem scale is comparable to the community scale. The study of ecosystems always involves addressing community and individual organism characteristics to some degree but, as should be apparent in this paper, the focus is more on energy, water, and nutrient fluxes rather than on species composition. Community and ecosystem research usually involves the study of relatively homogeneous stands that are more or less a few hectares in size, or processes that are important at that scale. At least two other scales can be studied as well, i.e., the landscape scale consisting of a mosaic of communities over an area of a square kilometer or larger (more or less), and the biospheric scale where data are collected for the whole earth.

Landscape studies have great relevance to ecosystem research, and vice versa. Using aerial photos, the tree ring record, and computer simulation techniques, Romme (1982) was able to date and map the occurrence and areal extent of fires during the last few centuries in a 73 km^2 tract of subalpine forest and meadows in Yellowstone National Park. He demonstrated how the proportion of this landscape in young, middle, and older stages of succession changed considerably through time (fig. 4). Romme is now working with Don Despain, Park Research Biologist, to determine if larger portions of the Park are in what has been referred to as a "shifting mosaic steady state" (Bormann and Likens 1979). Romme could find no evidence that fire suppression had affected the subalpine forest mosaic that he studied, primarily because large fires have occurred there at long intervals of 300-400 years and fuel accumulation since Park establishment generally has not been sufficient to support large fires. In a subsequent paper, Romme and Knight (1982) speculate on the implications of shifting mosaics for water and nutrient out-

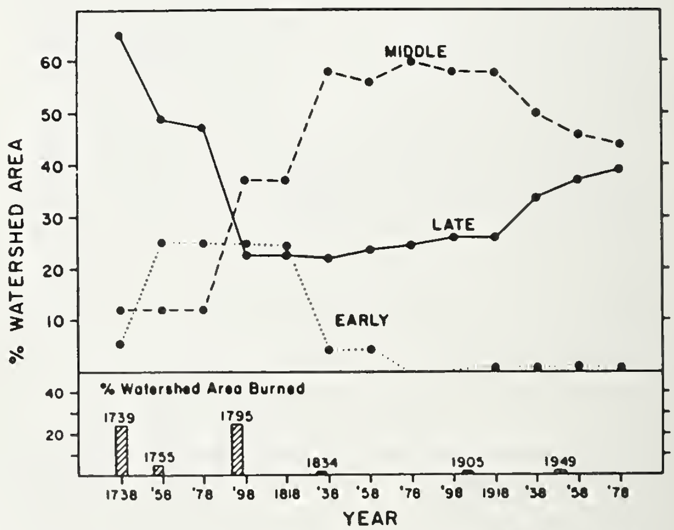

Figure 4.--Percent of a 73-km^2 area in Yellowstone National Park covered by forests in early, middle, and late stages of succession, and the percent of the area burned in a series of fires from 1738 to 1978. The shift occurring in the predominant successional stages suggests that the area is not in a "shifting mosaic steady state." From Romme and Knight (1982); reprinted with permission of the American Institute of Biological Sciences.

flow, lake productivity, song birds, and elk. Knight (1987) reviewed the effects of coniferous forest mosaics on flammability and the spread of parasites.

The landscape scale seems highly relevant to the management of National Forests and wilderness areas, since roads, campgrounds, timber harvesting, habitat improvements, and fire suppression are creating new mosaics. In some areas forest fragmentation is occurring (Harris 1984), while elsewhere there is the potential of landscape homogenization due to fire suppression (Habeck 1985). Landscape architects have been employed to design aesthetically pleasing landscapes, but what is the ecological impact of different landscape designs? Is there an ecological rationale for prescribing one vegetation mosaic over another? Optimal mosaics apparently can be designed for water yield (Leaf 1975) and for certain wildlife species (Thomas et al. 1976, Harris 1984), but less is known about the effect of the mosaic on, for example, biotic diversity, maintaining a certain level of primary or secondary productivity, the spread of fire or insect epidemics, and nutrient fluxes that could affect site productivity or streamwater quality. Large National Forests in the Rocky Mountain states provide excellent locations for such research because the landscape mosaics are being manipulated now and will be for many years to come.

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Partial Cutting in MPB-Susceptible Pine Stands: Will It Work and for How Long?

J. M. Schmid[1]

Abstract--Partial cutting in mountain pine beetle-susceptible stands shows promise in reducing tree mortality. Mortality appears to be least in the lower growing stock levels. RMYLD predicts GSL 80 and GSL 120 stands will remain unsusceptible for 40 to 50 years and < 20 years, respectively. The Berryman model predicts GSL 80 and GSL 120 stands will be highly and extremely susceptible within 10 years after cutting.

Silvicultural treatment of lodgepole and ponderosa pine stands shows promise in reducing tree mortality caused by the mountain pine beetle. Initial treatments removed the most susceptible trees (Cole and Cahill 1976)-- either by clearcutting or cutting the larger diameter trees (≥ 12 inches d.b.h.). When enough trees ≥ 12 inches were not available, then progressively smaller trees--trees ≥ 10 inches or ≥ 8 inches--were cut, depending on how much additional basal area or volume was to be cut. These treatments reduced MPB losses, because they removed all suitable host material. Such partial cuts may yield the most commercially desirable product, but generally are not totally satisfactory because they leave a less desirably stocked stand of poorer quality with uneven spacing, while removing the dominant, more rapidly growing trees.

To avoid these detrimental aspects, more recent cuttings have emphasized leaving regularly spaced, larger diameter trees of better form and well- developed crowns. Current studies are leaving growing stock levels (GSL) ranging from 40 to 120. In the Black Hills, ponderosa pine stands are being cut to GSLs from 60 to 100 on sites with SI < 65, and GSLs 80 to 120 on sites with SI ≥ 65 (fig. 1). In lodgepole stands in Colorado and Wyoming, GSLs of 40, 80, and 120 are being installed. In Front Range ponderosa pine, GSLs of 40, 60, and 80 will be tested where suitable conditions can be found.

For all of these cutting levels, two questions are being asked: (1) will they reduce MPB-caused mortality, and (2) how long will the treatment be effective? Evidence gradually forthcoming indicates that partial cutting will reduce MPB mortality, and the MPB mortality is least at the lowest GSL and greatest at the higher GSL (McGregor et al. 1987). Preliminary results in Wyoming indicated little mortality in a 100-leave tree cut (Cole et al. 1983). However, mortality should have been low in this test, because the leave trees were marginally susceptible (8 inches) and stand density was extremely low (GSL 40). Subsequent results from Oregon indicated the 18- by 18-foot or 21- by 21-foot spacings (lower GSLs) have less mortality than the 12- by 12-foot or 15- by 15-foot spacings (higher GSLs). GSL 80 and 100 partial thinnings in Montana showed greatly reduced losses (McGregor et al. 1987). GSL 120 treatments in the same area suffered losses similar to untreated stands, but spacing in them was not always uniform. These early results suggest partial cutting will reduce MPB losses, but they have spawned the further question of what level of cutting will yield minimal MPB losses and maximum timber production.

The second question--how long will partial cuts remain effective-- currently cannot be answered, except through model projections. Preliminary unpublished data from Oregon suggest at least 15 years is possible for stands with a mean diameter < 8 inches. For stands greater than 10 inches, the question remains unanswered, although studies in progress should ultimately answer this question.

Hypothetical answers can be derived by projecting development of recently cut stands through two models--RMYLD (Edminster 1978) and the Berryman model (Berryman 1978). If stands are assumed to become susceptible when their basal area (BA) reaches 150 square feet per acre (Sartwell and Stevens 1975), then RMYLD estimates stands cut to GSL 60 remain generally unsusceptible for 60 to 80 years, GSL 80 for 40 to 50 years, GSL 100 for 25 to 40 years, and GSL 120 for < 20 years (table 1).

One legitimate criticism of these projections is the precision of the assumption of susceptibility at BA 150. Although stands may be just as susceptible at BA 140 or 160, BA 150 is useful in comparing different GSLs until the relationship is more precisely defined.

Stand projections beyond 30 to 50 years seem irrelevant in view of Forest Service policy of achieving stands with a mean diameter of 12 inches at rotation ages of 100 to 120 years.

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Considering the stands used in these projections already have attained these objectives, concern for the duration of effectiveness seems questionable. However, full regulation of the commercial stands may not be achieved for another rotation because of the imbalance of age classes, so partial cutting of and concern for larger diameter stands is relevant.

The Berryman model rates stands as low, high, or extreme risk based on (1) the percent of the basal area with phloem thickness > 0.1 inch and stand resistance, where stand resistance equals the periodic growth ratio (PGR) divided by the stand hazard rating for trees older than 60 years. For computation purposes in this paper, data were taken from partially cut stands currently being studied. The stands are 100% ponderosa or lodgepole pine, and the phloem thickness is assumed to be > 0.1 inch on nearly 100% of the trees after 10 years. PGRs (PGR = radial growth last 5 years divided by radial growth for the 5-year period prior to the last 5 years) equal to 1.0 and 1.2 are from unpublished thinned stand data. Stand hazard rating (SHR) equals crown competition factor (CCF) times percent of the stand in pine (PLPP) divided by 100 (SHR = CCF x PLPP/100).

Figure 1.--Ponderosa pine stands (A) GSL 80 and (B) uncut.

Table 1.--Time and stand conditions when partially cut stands reach a basal area of 150 square feet per acre as projected by RMYLD.

Area/growing stock level	Conditions after thinning		Conditions when BA ≥ 150 (RMYLD)	
	mean D	BA	Time	mean D
	Inches	feet/acre	years	Inches
Brownsville (PP)				
60	12.4	60.5	76	19.5
80	11.5	80.8	51	15.7
100	12.8	100.7	37	15.6
Hinman (LP)				
80	12.8	79.8	40	17.6
100	12.7	101.2	27	15.5
120	10.9	118.1	13	12.3
Brush Creek (LP)				
40	9.8	40.0	90	19.6
60	12.0	60.7	62	19.9
80	10.0	81.3	40	13.6
120	8.9	119.7	16	10.2

The Berryman model indicates that GSLs 100 and 120 are highly or extremely susceptible 10 years after cutting (table 2), regardless of the PGR. GSLs 40 and 60 generally rate low in susceptibility for 20 years when PGR = 1.2 but tend toward high susceptibility when PGR = 1.0. For 10 or so years after cutting, PGR may approach 1.2 but within 10 to 20 years, PGR declines toward 1.0. Thus, PGR is significant only for the short-term, because it tends to stabilize. Later PGR will decrease as competition begins. The most important factor in the model appears to be the crown competition factor, which is mainly a reflection of tree diameter and growth.

The Berryman model and RMYLD projections both indicate that higher GSLs (100 to 120) become susceptible before the lower GSLs (40 to 60). However, the Berryman model

Table 2.--Time for partially cut stands to become susceptible[1] according to the Berryman model.

Area/growing stock level	Risk rating			
	PGR = 1.0		PGR = 1.2	
	10 years	20 years	10 years	20 years
Brownsville (PP)				
60	Low	Low	Low	Low
80	High	Extreme	High	High
100	Extreme	Extreme	High	High
Hinman (LP)				
80	High	High	Low	High
100	High	Extreme	High	High
120	Extreme	Extreme	Extreme	Extreme
Brush Creek (LP)				
40	Low	Low	Low	Low
60	Low	High	Low	Low
80	High	Extreme	High	High
120	Extreme	Extreme	Extreme	Extreme

1Low = low susceptibility; High = high susceptibility; Extreme = extreme susceptibility.

seems to project stand becoming susceptible earlier than RMYLD does. Eventually, data from these silvicultural studies will validate which model most accurately predicts the duration of effectiveness, and may redefine our susceptibility levels.

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The Measurement of Changes in a Colorado Subalpine Ecosystem Resulting from Alternative Recreation Camping Behaviors

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A principle of wilderness management is to use the "minimum tool" necessary to control recreation use (Hendee, et al. 1978). This principle is based on the public perception and desire to have opportunities in wilderness that are characterized by lack of restrictions, freedom, spontaneity and escape from daily work lifestyles. Hence, federal land managers often prefer to employ less regulative actions; those which indirectly alter human behavior (e.g., information or education) as opposed to those which directly regulate human behavior (e.g., party size or designated campsites).

In favor of the "minimum tool" management approach, federal land agencies have begun a large scale information and education campaign entitled, "Minimum Impact Camping". The intent is to educate recreationists as to how they can minimally impact natural areas. The hope is that (1) increased awareness and knowledge will lead to (2) altered or appropriate human behavior which will lead to (3) minimal alteration of ecosystem processes and quality of appearance.

Focus of the Study

It is generally assumed that the amount of impact in a subalpine ecosystem will be less if recreationists follow prescribed minimum impact camping behaviors (MICB) rather than traditional impact camping behaviors (TICB). In this study: MICB is defined as camping without a campfire (stove only); where such living activities as cooking, eating and relaxing are dispersed away from the tent; human artifacts (trash, log or rock seats) are not apparent; and soft soled shoes are worn in camp. TICB is defined as camping with a campfire; where such living activities as cooking, eating and relaxing are concentrated around the campfire; human artifacts are likely (rock fire ring, woodpile, rock or log seats, trash in firepit); and camp shoe type is of individual choice. Light use campsites are defined as having no previous recreation use through 9 nights use per year.

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The study compares the effect of two alternative camping behaviors, MICB and TICB, to establish the functional relationship between: (1) amount of use and amount of impact, (2) human behavior and system modification at light use subalpine campsites. More specifically, the hypotheses are:

1. The amount of impact is greater for the TICB treatment than for the MICB treatment.
2. There is no treatment time interaction for each of the weekly treatment applications.

The research design incorporates MICB and TICB treatments administered over a 2 year monitoring period during the summers of 1986 and 1987. This is a progress report summarizing the results of the first year of the study, an assessment of the changes that occurred throughout the 9 treatments and how these changes relate to the type of recreational behavior at each site.

Related Research

Detailed studies of wilderness campsites are few. Most impact studies have centered on developed campsites accessible by car receiving much heavier use. Wilderness campsite condition studies have been conducted in northern Minnesota (Merriam, et al 1973; Frissell and Duncan 1965), the eastern United States (Leonard, et al 1983; Bratton 1978), Oregon (Cole 1982), Idaho (Coombs 1976), and Montana (Fichtler 1980). Of these studies, only Cole (1982), Fichtler (1980) and Coombs (1976) begin to quantify low use data.

Previous studies of wilderness campsite deterioration concentrated on documenting vegetation cover losses through mechanical damage; i.e., trampling studies (Emanuelsson 1979; Liddle 1975; Burden and Randerson 1972) and soil deterioration at campsites (Leonard and Plumley 1979; Legg and Schneider 1977). Live tree damage, mutilations and scarring was reported by Cole (1982). Seedling loss was reported by Cole (1982), Coombs (1976) and Fichtler (1980). Cole (1982) concluded that prevention of seedling elimination may be most critical due to loss of future overstory.

Conclusions about the relationship between use and impact vary. Frissell and Duncan (1965), working in the BWCA, found no relationship between amount of use and either vegetation loss or bare ground. Merriam, et. al. (1973), also working in the same area, found a more consistent relationship between vegetation loss and amount of impact when sites were stratified by vegetation type. Cole (1982) reported that the response of variables as use increases is poorly understood, especially in the light use portion of the impact/amount of use spectrum.

A partial explanation for the difference in results may lie in the method of analysis employed by individual researchers. The functional relationship between impact and use is hyperbolic rather than linear; i.e., the rate of impact increase decreases as use increases (Cole 1982). Also, the amount of impact is not the same for every variable. Typical research results relating campsite impact variables and amount of use show an exponential increase in impact levels from light use, less than 5 nights per year to moderate use, estimated at 10 to 20 nights per year (Cole 1982). Coombs (1976) found the most pronounced differences among sites (light, moderate, and heavy use) to occur between light use and moderate use sites.

Study Area

The Comanche Peak Wilderness was selected for study because of its proximity to Fort Collins, as a primary source of treatment volunteers; location where recreation and other social uses could be controlled; visitor use patterns similar to other eastern slope wilderness areas; and the representativeness of the are to the many glaciated, mountainous wilderness areas in Colorado and the central Rocky Mountain region.

The Comanche Peak Wilderness is located along the north and northeast boundary of Rocky Mountain National Park in the Mummy Range, encompassing 27,316 ha of the Roosevelt National Forest in north central Colorado. The terrain, in general, consists of a high rolling plateau at approximately 3350 meters in elevation, reaching 3810 meters at Comanche Peak.

Study Site Selection Criteria

Subalpine lakes are a primary destination for most visitors to the Comanche Peak Wilderness. Brown's Lake, at 3180 meters elevation, typically receives 30 visitor days of use each weekend during the summer (personal observation). Unauthorized public use of study campsites was controlled for by locating sites one mile away from Brown's Lake, a major destination point/water supply source, and by locating sites off the main travel route, the Brown's Lake Trail. Further, study sites were unobtrusively posted and roped off in the event that a site was discovered by the public.

Environmental differences were minimized by selecting sites located within the same drainage, on a south facing aspect on soils derived from granitic bedrock. All sites are within the *Descampsia caespitosa* association. This permits the effects of alternative camping behavior to be measured more precisely. Control sites are located in the vicinity of each treatment plot in order to determine measures of natural variation. All measurements on control plots are identical to measurements on treatment plots.

Field Methodology

In order to estimate the amount of change and rate of change that occurs on each treatment site, it is important to begin weekly measurements from a permanent starting point. Therefore, the data collection procedure utilizes the point method, where the quadrat is reduced to an infinitely small point and permanent starting/ending points are located between baselines. In practice, a point frame is held perpendicular to the ground and sharp tipped metal pins are lowered until intercepting vegetation, litter or bare ground. Each plot is measured systematically by extending 11 line transects from the permanent baseline points. Basal point measurements are taken every 10 cm along each transect. These measurements yield unbiased estimates of cover, frequency and density.

The following categories of vegetation cover variables are measured weekly for each treatment and control plot: forb, grass, grass like, shrub, tree, ground cover (mosses and lichens), litter, bare ground and rock. Human artifact development, i.e., fire ring, ash, woodpiles, trash, rock or log furniture, and loss of downed wood, are measured on treatment sites.

A count procedure is used to measure tree seedlings, live tree mutilations/scarring, loss of downed wood and human artifact development. All human artifacts are left in place from treatment to treatment in order to monitor manipulative activity.

Each treatment site is partitioned according to vegetation/visual impact zones developed as a result of alternative behavioral patterns. Five zones are delineated: vegetation erect (no recreation activity); vegetation flattened and green (tent site); vegetation flattened and brown (concentrated activity); litter; bare ground. Post test measures of soil physical properties (bulk density, percent moisture) and biomass within each impact zone provide additional estimates of covariance within and between treatments.

Volunteer Selection

Potential camping volunteers are interviewed and assigned to either the MICB or TICB group, depending upon their level of camping behavior knowledge and experience. Three teams of 2 people comprise each group. Participants are escorted in separate groups to their respective campsites. Both groups are informed that they are participants in an elk human interaction impact study. Participants are requested to confine their living activities (cooking, eating, relaxing) to the study site in the evening hours in order to equalize time spent at each campsite.

Preliminary Results

Data collection is still in progress at this point (Summer 1987), but several relationships have been observed. The reader is cautioned about relying on the preliminary observations, pending the complete quantitative analysis of data.

Traditional Impact Sites

Manipulative behavior includes (1) the building of a rock fire ring, (2) construction/stocking of a woodpile and (3) the general "humanizing" of the area by arranging logs or rocks to form a fire circle or the removal of tufts of grass to form a smoother tent site. Measurement variables directly affected by manipulative behavior include human artifacts, loss of downed wood and changes in herbaceous vegetation/bare ground area.

The greatest amount of change occurred during treatment weeks 1 and 2 as a result of manipulative behavior patterns. During this period, the fire ring was constructed from nearby rocks, onsite downed wood including branches from logs too big to move were broken off to form a woodpile, and logs were carried onto the site to form benches around the fire. During treatments 3 through 9, manipulative behavior was less evident, mainly consisting of restocking the woodpile or making minor changes in the position of the log benches that formed the fire circle.

A circular impact pattern centered on the fire ring developed even though the campsites were rectangular. The rate of impact per treatment was greatest for herbaceous vegetation within the fire circle and at tent entrances. It is speculated that the wearing of lug soled shoes in camp impacted tent entrance areas more forcefully than soft soled shoes, resulting in bare ground formation. Within the fire circle, the amount of bare area increased from .4 m2 after treatment 2 to 1.6 m2 after 4 treatments. Further, the vegetation/visual impact rating within the fire circle dropped from an impact level of flattened and green after 1 treatment to flattened and brown after 4 treatments. The mean vegetation/visual impact zone ratings for traditional impact sites 1, 3, and 6 after 4 treatments were estimated as: bare ground, 2%; litter, 6%; vegetation flattened and brown, 25%; vegetation flattened and green, 44%; and vegetation erect, 21%.

During treatments 5 through 9, expansion of the impact zone areas bare ground and litter were observed within the fire circle. The overall appearance of the site continued to deteriorate visually from off site areas. Vegetation became flattened across the whole site with the exception of untrampled islands, whereas, offsite vegetation remained erect.

Minimum Impact Sites

The amount of impact appears to be cumulative on minimum impact sites for the variables: herbaceous vegetation and bare ground. The greatest amount of change occurred at tent entrances. A bare area 0.4 m2 developed after the fifth treatment on site 5. It is speculated that this was the most popular position for the tent entrance. It was also noted that at this site the vegetation appears less "vigorous" due to lower soil moisture levels. The effect of soil moisture levels and vegetation response to impact will be monitored further.

Minimum impact sites 2 and 4 did not develop bare ground areas, as exhibited on site 5. The mean vegetation/visual impact ratings for minimum impact sites 2, 4, 5 after four treatments were estimated as: vegetation flattened and brown, 1%; vegetation flattened and green, 33%; and vegetation erect, 66%.

Conclusions

Many questions remain unanswered at this stage of the project. The second year of the study will hopefully help to delimit the relationships among type of camping behavior, amount and rate of impact, and the carrying capacity at wilderness campsites.

It appears that manipulative behavior, i.e., the building of a fire ring on traditional impact campsites, accounts for greater amounts of impact over a shorter time period because activity is concentrated around the fire ring. Whereas, on minimum impact campsites manipulative behavior is lacking, resulting in less severe vegetative and visual impacts. The greatest amount of change on minimum impact sites occurs at tent entrances where bare ground areas may develop due to concentrated activity.

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245 The Application of Video/Photographic Remote Sensing to Recreation Resource Management: An In-Progress Report //

John R. Watson, Glenn Haas, and James K. Lewis[1]

Abstract--Increasing recreational impacts upon our natural resources is occurring during periods of both fiscal austerity and strict environmental mandates. Thus, alternative methods are needed to aid resource managers in their decision making. New advances in video and photographic remote sensing technologies may help compensate for this dilemma. This current project will contrast satellite, video/photographic, and ground truth data from alternative passages of hikers, horse-back riders, and off-road vehicles in prairie and subalpine ecosystems. Additionally, recent developments in image processing will be tested for their relevancy to recreation resource management.

Since the late 1960s, recreational use and resource demands have steadily increased on the 700 million acres administered by federal and state public land agencies. Concomitantly, the promulgation of environmental legislation along with budget cuts have strained the conventional methods of data acquisition which managers have heretofore utilized to monitor and ameliorate recreational impacts. It is our contention, that new user friendly remote sensing advances and geographic data handling systems can aid in compensating for this growing dilemma.

Since 1980, the adoption of high quality yet low cost "off the shelf" video components for remote sensing has been growing with encouraging results (Curran, 1982; Everitt and Nixon, 1985; Meisner, 1986; Nixon, et al., 1985; Schumacher, 1980; Vleck, 1983). Reduced video resolution remains a problem and most video systems continue to use conventional aerial photographs for comparison purposes. Also, 35mm slides can now be digitized and converted to a video signal for processing. However, higher resolution video cameras and recorders will be on the market shortly. The advantages of video are the near real time imagery with immediate turnaround time, low cost of tape, and its compatibility with electronic data handling systems. In addition, recent advances in video image processing hardware and microcomputer software programs will allow anyone access to the technology (i.e. video-game difficulty).

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In this instance, our research program is directed to develop and export remote sensing systems as practical, easy to use tools which any resource manager could utilize in their decision making. Thus, professionals who have no experience or interest in remote sensing, computer or image processing theory could use this system in a practical problem solving manner. It must be stated that while this technology represents a promising approach to recreational resource monitoring, it will not replace ground monitoring efforts. However, as stated by Anderson et al., (1980), "one of the major benefits of surveys supported by remote sensing, compared with those based only on traditional groundwork, is the capability to extrapolate information from sample sites to unsampled, remote areas."

Background

In January 1987, our McIntire-Stennis project (Watson and Haas, PI's) entitled "A convergent validation study utilizing video and photographic remote sensing techniques for the assessment of recreational-induced impacts" pooled resources with a NASA project (James Lewis, PI-CSU; Lee Miller, PI-U of Nebraska) entitled, "Modeling energy flow and nutrient cycling in natural semi-arid grassland ecosystems with the aid of thematic mapper data." In both studies, a multistage sampling scheme is underway consisting of ground truth data (stage 1), low flying aircraft for video/photographic data (stage 2) and satellite thematic mapper data (stage 3). Both of these projects are currently underway at the ARS Central

Plains Experimental Range (CPER) within the Pawnee National Grasslands in Colorado. In addition, the McIntire-Stennis project will be duplicated, minus stage 3 sampling, at a subalpine site during the summer of 1988.

Experimental Procedures

Ground Truth

Over two summer periods, ground data will be collected at each study site, respectively (prairie 87 and subalpine 88) before and after each imagery session. At each study site five, contiguous, rectangular plots are established and non-overlapping treatments applied similar to those of Weaver and Dale (1978) comparing different levels of trail travel impacts upon grasses caused by hikers, horses and trail bikes. A randomized complete block design is used to reduce confounding from plot gradient bias. Experiments at both study sites will be replicated for each treatment (hiker, horse, off-road vehicles) at low (100,300), medium (500,700) and high (1000,1200) trampling passages.

Five transects are located equidistant across each trail where one meter quadrats are placed at trail center for sampling. Prior to treatment application and at all treatment levels, the following parameters are being examined: percent bare ground; trail width; trail depth; herbaceous biomass; total chlorophyll; and spectral reflectivity. This information will then be correlated with the remote sensing data.

Remote Sensing

A Xybion[2] MSC-02 solid state multispectral video camera is being used which has the unique capability of sequentially capturing images in up to six different user-defined spectral regions. This is accomplished through the use of a rotating filter system between the lens and the CCD imager. This system contains a user-changeable filter wheel with six different filters. Four of the filters closely match the band pass of the first four landsat bands. One filter removes wavelengths longer than 0.43um and the last one allows the full range of sensitivity of the camera to be imaged (0.4um - 1.1um). The lens is a Nikkor[2] 20mm f2.8 in a C to Nikon[2] adapter.

The Xybion is interfaced with a portable Panasonic[2] AG 2400 portable VHS recorder with a JVC[2] TM-22U portable monitor. In addition, the aerial package contains a Spectron[2] CE 590 spectroradiometer allowing measurement of 256 reflectance bands with each of two Spectron CE 390 heads with 1 field of view (wide band .400 to 1.080um and a UV .200 to .440um). A portable oscilloscope is also included. For ground truthing, the Spectron can measure 1 cm^2 homogeneous areas with the 1 lens and larger plots with a 10° lens from a tripod at the quadrat sites in each treatment area. This will allow statistical comparison of reflectance data among treatment means and for comparison with aerial reflectance data. Lastly, a 35mm Nikon[2] F3 with an MD-4 motor drive and Nikon[2] 105mm f2.8 lens is being used in conjunction with the video system.

An aircraft mount was built to fit on the seat rails of any Cessna and extend out the right door (fig 1). In this case it is a Cessna 210 turbo owned by CSU flown with the right front seat removed and a modified right front door allowing the instrument package to stick out the bottom portion. The mount holds the video camera, one spectroradiometer head, and one Nikon camera. An instrument rack is mounted in place of the left seat in the second row of the aircraft. This rack holds the video recorder, the video monitor, the spectron CE 590, and the oscilloscope. The instruments were bore sighted and temporally synchronized using a battery-powered relay separated from the spectroradiometer data analyzer with a diode. This relay energizes all instruments, the camera trigger on the CE 590 starts the video and triggers the Nikon as the spectroradiometer cycles. Cycling continues with one scan and a 35mm exposure every 7 seconds until the magnetic tape on the CE 590 is full or until 36 exposures have been made on the Nikon. A digitizer board from Xybion (ImCap 01) will be used with Xybion software to digitize and display the video images on an Electrotome2 ECM 1311 color monitor.

The Mapping and Image Processing System[2] (MIPS) developed by the NASA project co-investigator (Lee Miller) using a Vectrix[2] VXPC-B graphics controller will be used for video image and data processing. This software represents the user friendly interface between the remote sensing technology "mystique" and the basic information needed for resource management applications. MIPS can be retrofitted to IBM[2] PC compatible microcomputers and has a wide range of functions (including GIS mapping features) for specific analyses of satellite, video and photographic imagery. In this study, detection of trampling impacts will be analyzed using MIPS. The MIPS software would produce an appropriate picture on the monitor of the impacted scene from the remote sensing tapes or digitized slides. Either the entire scene or subscene may then be examined. For example, with color infrared film we could compute the area selected into a 10 step green biomass map, color coded and displayed with appropriate areas for the 10 levels. Certain levels would represent the impacted areas. Features mapped are reported in percent, acres or some other measurement unit selected by the user. This process is accomplished with a mouse which can direct a special cursor to one special area on the screen. That prototype pixel trains one of the systems algorithms to identify other similar pixels throughout the scene (which could represent many acres). Those pixels matching the prototype are then color coded and measured (fig. 1d).

[2]The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.

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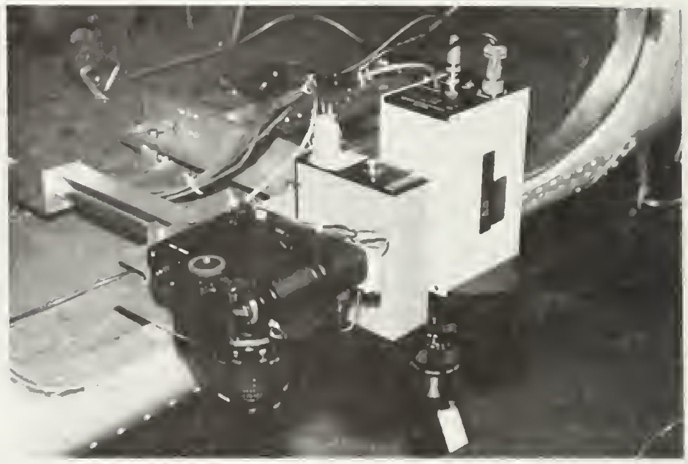

Aircraft Instrument Package (a,b), 35mm

Natural Color Image, October 1986 (c)

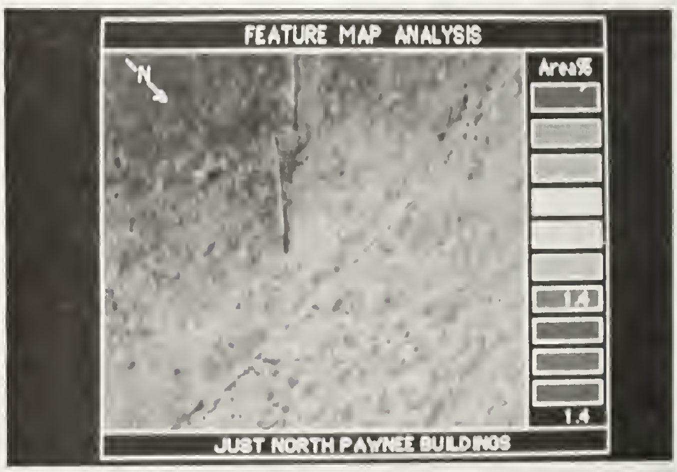

Image in (c), Digitized and Classified (d)

Figure 1.--Photograph (a) shows Cessna aircraft with right door removed to accomodate the floor camera mount. Photograph (b) shows the instrument package - from left to right, Nikon F3 35-mm, Spectroradiometer, and Xybion multispectral video camera. Photograph (c) is a 35-mm (3400' AGL) image of a shortgrass prairie site, outlined areas is magnified in image (d). Outlined area from photograph (c), digitized and displaying a bare soil classification.

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Factors Affecting Snowmelt and Streamflow

W. U. Garstka[1]

The excellent collaboration between the Bureau of Reclamation and the Forest Service, as evidenced by a report on the Cooperative Snow Investigations at the Fraser Experimental Forest,[2] had its inception at the "First Conference of Engineers" of the then newly organized Reclamation Service, which was held at Ogden, Utah, September 15 to 18, 1903.

Gifford Pinchot, Chief Forester of the Forest Service, spoke at this conference, and his presentation is quoted in part as follows.

> "For the present, much of the most important use of the forest reserves is to supply water to the irrigator, and their utility in this respect should be preserved in every possible way. This use, too, will increase with time, and it will become more and more evident that the foundation of the irrigation development of the West lies in the wise administration of the forest reserves. Not only can the present supplies of water be conserved by the right handling of the forest, but there is no question whatever that in many localities they may be largely increased."

Although few men are alive today who comprised the Reclamation Service and the Forest Service on the date when Gifford Pinchot attended the meeting at Ogden, the basic concepts on the development of natural resources that inspired the workers of that day stand forth today with undiminished brilliance as guiding lights in the endeavor to attain more intensive and efficient utilization of the Nation's water resources.

The report on the Cooperation Snow Investigations summarized the work done and the analyses made with data collected at the Fraser Experimental Forest, Fraser, Colo., during the snowmelt seasons of 1947 to 1953, inclusive. The Bureau of Reclamation and the Forest Service collaborated in these cooperative snow investigations. Comparisons between the catch in Sacramento-type storage precipitation gages and the accumulation of snow on the ground indicated that the gage catch was generally deficient. Charts compared degree-days computed from daily maximum and minimum temperatures with degree-days indicated by thermograph traces. Analyses of the runoff hydrographs showed the major importance of long-term recession flows in the snowmelt hydrograph. Relations were developed between the daily snowmelt hydrograph and the melt-causing meteorological factors that led to the development of techniques for forecasting the shape of the snowmelt hydrograph on a daily basis. The relation of area of snow cover to the resulting hydrograph was explored for 1 year when detailed mapping of the snow covered area was pursued. The effect of evaporation during the snowmelt season was analyzed by use of Light's equation.

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U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

Rocky Mountains

Southwest

Great Plains

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

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